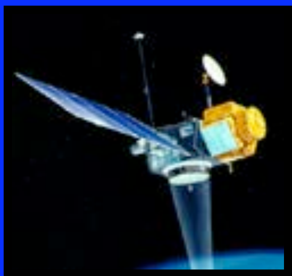
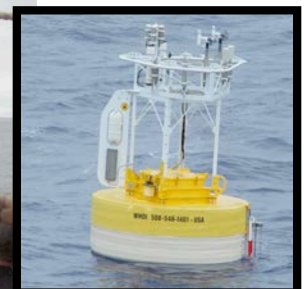
Annual Report




The State of the Ocean
and the
Ocean Observing System
For Climate









Fiscal Year 2005

Office of Climate Observation
Climate Program Office
National Oceanic and Atmospheric Administration

ANNUAL REPORT ON THE STATE OF THE OCEAN AND THE OCEAN OBSERVING SYSTEM FOR CLIMATE

FY 2005

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Acknowledgments

The editors wish to acknowledge the invaluable assistance of several colleagues, at the NOAA Office of Climate Observation, whose efforts were instrumental in completing this report. Yasunori Hanafusa, on assignment to OCO from the Japan Agency for Marine-Earth Science and Technology, volunteered long hours, far beyond the call of duty, to meticulously review and format many sections of the text. Todd Pearce provided the IT support that allowed us to exchange draft chapters with authors and to communicate among ourselves. Craig Joyner, and Keith Hayes provided much needed assistance with perplexing software, and Jonathon Brooks indefatigably coerced uncooperative computers back to life when large files brought them to their knees. We are grateful to these modest and helpful professionals for doing so much of the hidden work that was necessary to bring this report to fruition.

ANNUAL REPORT ON THE STATE OF THE OCEAN AND THE OCEAN OBSERVING SYSTEM FOR CLIMATE

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Foreword

The Office of Climate Observation is pleased to present the Fiscal-Year 2005 Annual Report on the State of the Ocean and Ocean Observing System for Climate. This effort is intended to be primarily an internal management tool but it is hoped that the Annual Report may develop over the next few years into an authoritative public record of the progress of the global observing system and its effectiveness in documenting the ocean's contribution to our Earth's changing climate.

Many people have contributed to this report either directly or indirectly, including scientists, engineers, technicians, researchers, teachers, and students at laboratories, universities, and oceanographic and atmospheric centers and institutions. The officers, crews, and volunteers on board the vessels where the fieldwork occurred played a major role as well. This document is a collaborative effort produced by a dedicated team of individuals focused on learning more about the influences of our oceans on climate.

The plan for implementing the global ocean observing system has been developed and agreed internationally, and we have taken great strides as a global community to fulfill the long-term goals that will achieve this monumental effort. We are proud to be part of the NOAA team that has worked closely with partners from more than 60 nations to bring the global observing system this far.

During FY 2005 incremental advancements were made across all of the observing networks and two particularly significant milestones were achieved. First, the Global Ocean Observing System passed the 50% completion mark, advancing by 7% from 48% to 55% complete. Second, on 18 September 2005, Global Drifter 1250 was ceremonially deployed near Halifax in conjunction with the second session of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology. With this deployment, the global drifting buoy array reached its design goal of 1250 data buoys in sustained service and became the first component of the Global Ocean Observing System to be fully implemented. Eighty-seven representatives from 16 countries participated in the celebration. The central image on the cover of this year's Annual Report commemorates this historic milestone.

The Office of Climate Observation is convinced that the accomplishments outlined within this report will help the global community understand more clearly and quantitatively the role of the oceans in our Earth's ever-changing climate system. We look forward to the future as we unravel the mystery of our oceans together. It is with great pleasure that we present this work.

Mike Johnson
Director, Office of Climate Observation
March 2006

Program Plan
for
Building a Sustained Ocean Observing System for Climate

Office of Climate Observation
Michael Johnson

Updated: March 2006

Overall Summary

The mission of the Office of Climate Observation is to build and sustain a global climate observing system that will respond to the long term observational requirements of the operational forecast centers, international research programs, and major scientific assessments. Although the U.S. Climate Change Science Program (CCSP) has identified the critical need for the federal government to deliver regular reports documenting the state of Earth's climate, an observing system does not presently exist that is capable of accurately documenting climate variability and change. Through this program plan NOAA will develop the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system and to deliver regular reports on the adequacy of the system in documenting the ocean's contribution to climate.

1.0 Base Program

1.1 Key activities currently carried out by NOAA for this strategy area: Over the past decade NOAA has worked with national and international partners to begin building a sustained global ocean system for climate, focusing first on the tropical Pacific, and expanding to the Atlantic and the Indian Oceans. It is now well understood that documenting and forecasting climate will require continuous measurements from space along with the instrumenting of the entire global ocean. The present international effort is about 55% of what will ultimately be needed for the global system. NOAA presently maintains approximately 50% of the *in situ* networks and 30% of the space components and is committed to the goal of providing at least 50% of the composite system over the long term.

The existing foundation is comprised of twelve complementary *in situ*, space based, data and assimilation subsystems: 1) Global Tide Gauge Network; 2) Global Surface Drifting Buoy Array; 3) Global Ships of Opportunity Network; 4) Tropical Moored Buoy Network; 5) Argo Profiling Float Array; 6) Ocean Reference Stations; 7) Ocean Carbon Monitoring Network; 8) International Arctic Ocean Observing System; 9) Dedicated Ship Operations; 10) Satellites for Sea Surface Temperature, Sea Surface Height, Surface Vector Winds, Sea Ice, and Ocean Color; 11) Data and Assimilation Subsystems, and 12) System Management and Product Delivery. The system design is illustrated in Figure 1. This is an international effort. The system illustrated in Figure 1 represents the common goals and objectives of the international Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), the Global Earth Observation System of Systems (GEOSS), the U.S. Integrated Ocean Observing System Global Component (IOOS), and well as NOAA.

The plan is being advanced by NOAA via matrix management within the Climate Goal. Implementation of the in situ networks is through distributed centers of expertise at the NOAA Research laboratories, the National Ocean Service Center for Operational Oceanographic Products and Services, the National Data Buoy Center, and the university laboratories that have developed the instruments and techniques. The space and data components are centered in the NOAA Environmental Satellite, Data and Information Service. The space components are being advanced via other NOAA program planning; they are described here because of their central role in global observation but they are not detailed in this plan. The focal point for developing global ocean data assimilation capabilities is the Geophysical Fluid Dynamics Laboratory in partnership with the National Centers for Environmental Prediction and university-based applied research centers. The system management functions are focused in the Office of Climate Observation.

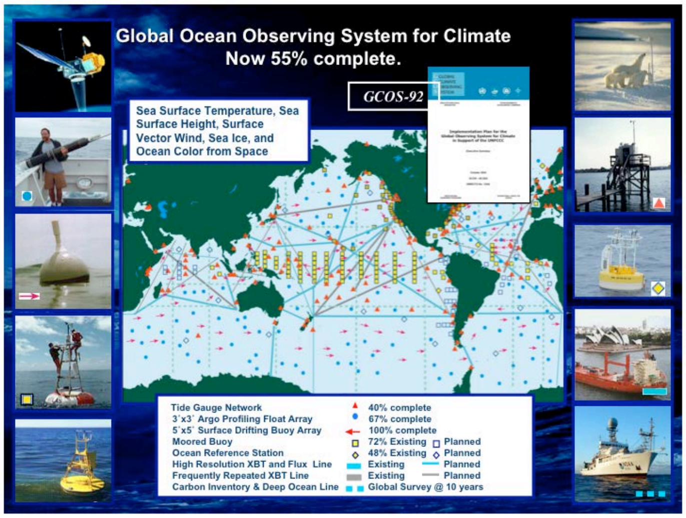

Figure 1.

1.2 Budget and funding history for each of the major activities ($K)

Network		FY 02	FY 03	FY 04	FY 05	FY 06
Tide Gauge Stations		670	710	970	1196	1177
Drifting Buoys		1699	2077	2769	3130	3427
Tropical Moored Buoys		3175	3175	3625	4360	3094
Ships of Opportunity		1960	1903	2487	2907	2776
Argo Profiling Floats		271	275	273	249	247
Ocean Reference Stations		1712	2082	2998	2995	3958
Ocean Carbon Networks		1478	2204	2875	3521	3482
International Arctic Ocean Observing System		337	337	337	397	310
Dedicated Ship Time		0	626	523	92	542
Data & Assimilation Subsystems		1286	1323	1487	1418	1331
Service Argos Data Processing		813	480	1525	1408	448
Product Deliver, Analysis/Reanalysis		578	638	896	1982	2048
Institutional Infrastructure		626	653	1269	1356	711
IOOS Global Systems Total (OCO managed)		14605	16483	22034	25011	23551
Argo Program		6978	9706	9811	9491	9758
Arctic Program		1600	4322	3651	4928	4927
TAO/PIRATA, NWS operations		0	0	0	0	3200

2.0 Statement of Need

The *Second Report on the Adequacy of the Global Observing System for Climate in Support of the UNFCCC* concludes “there has been progress and improvement in the implementation of global climate observing systems since the first report, especially in the use of satellite information and in the provision of some ocean observations. At the same time, the Report notes that the global terrestrial networks remain to be fully implemented; the ocean networks lack global coverage and commitment to sustained operations; and the atmospheric networks are not operating with the required global coverage and quality. The Report concludes, in agreement with the IPCC, that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. …Without urgent action to address these findings, the Parties will lack the information necessary to effectively plan for and manage their response to climate change."

The Report goes on to note "new technology developed and proven by the ocean climate programs of the 1990s has allowed the ocean community to design and commence implementation of an initial ocean climate observing system that is well focused on the UNFCCC needs. The first priority is the full implementation of this system together with its associated data, analysis and product capabilities."

In response to the Adequacy Report, the international community published the GCOS *Implementation Plan for the Global Observing System for Climate in support of the UNFCCC* (GCOS-92) in October 2004. This implementation plan details the actions needed to achieve global coverage by the ocean networks. The system put in place for climate will also support global weather prediction, global and coastal ocean prediction, marine hazard warning, marine environmental monitoring, and many other non-climate users.

This program plan is founded on the international design noted in GCOS-92; it is illustrated in Figure 1. Other requirement drivers include the CCSP Strategic Plan expressing need for "complete global coverage of the oceans with moored, drifting, and ship-based networks," and the US National Oceanographic Partnership Program's *First U.S. Integrated Ocean Observing System (IOOS) Development Plan* which lists as a primary objective: "Continue implementing the global ocean-climate component of the IOOS (important for addressing the goals of climate change, maritime operations, and natural hazards)." NOAA's contribution to global implementation is represented in the program budget and the progress to date is illustrated in Figure 2. Implementation of this program plan will demonstrate to the world community that the United States is intent on taking immediate action to address the Second Adequacy Report findings, is willing to play a leadership role in achieving global coverage of the ocean networks, and is committed to sustained operations.

2.1 Program requirements to be met: The NOAA Climate Goal is organized into five Programs: 1) Climate Observations and Analysis; 2) Climate Predictions and Projections; 3) Climate Forcing; 4) Climate and Ecosystems; and (5 Regional Decision Support. This plan describes the "ocean subcapability" of the Climate Observations and Analysis Program.

2.2 Input from NOAA leadership related to this strategy: This program plan addresses NOAA's Strategic Plan, Climate Strategies, and the Annual Guidance Memorandum. In particular:

- Strategic Plan: Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship.
- Climate Strategies: Improve the quality and quantity of climate observations, analysis, interpretation, and archiving by maintaining a consistent climate record and by improving our ability to determine why changes are taking place.
- Annual Guidance Memorandum: The Integrated Ocean Observing System (IOOS) must be developed as a major component of the U.S. contribution to the Global Earth Observation System of Systems (GEOSS).

2.3 External constituent input related to the strategy area: In 2001 the U.S. GOOS Steering Committee conducted a formal review of the 2001 version of this program plan. The review panel

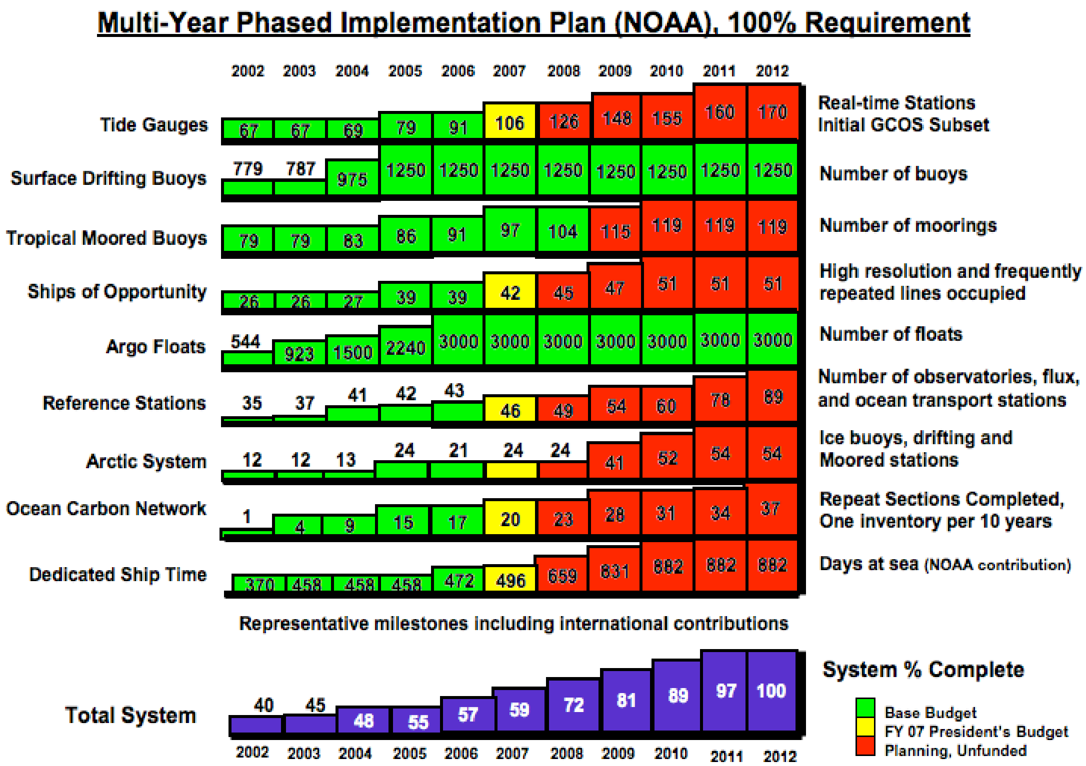

Figure 2.

included international representatives of the IOC, IGOS, CLIVAR, WOCE, OOPC, GODAE, and JCOMM as well as partner agencies within the United States – NASA and NAVOCEANO. The seven summary recommendations of the review are paraphrased below.

1. Strong overall support for the plan. U.S. GOOS urged NOAA to implement the plan with the following additional recommendations:
2. The need for a management plan – An effort of the proposed magnitude must be integrated, organized, and managed as a system in order to be effective. The management plan should define an orderly decision making process with management accountability that is understood by other agencies and by customers. A single NOAA point of responsibility and authority is very desirable. Sections 7.0–7.8 achieve this recommendation.
3. The need for a data and information management budget. Section 6.12 achieves this recommendation.
4. The need for improved ocean products – evaluation and delivery. Sections 7.0-7.8 achieve this recommendation.
5. The need for transition to operations of precision altimetry. Section 6.11 achieves this recommendation.
6. The need for ocean carbon monitoring to be better defined. Section 6.8 achieves this recommendation.
7. The need to deal with dedicated ship time issues. Section 6.10 achieves this recommendation.

2.4 Relevant Congressional input or guidance related to the strategy area: The FY03 Senate Committee on Appropriations Report "reaffirms its support for the establishment of an integrated, interagency ocean and coastal observing system … and requests the submission of a plan to implement such a system." The National Oceanographic Partnership Program's Ocean.US office responded to this Congressional request on behalf of the contributing agencies by publishing in 2005 the *First U.S. Integrated Ocean Observing System (IOOS) Development Plan*. The observation system detailed inthis program plan forms the nucleus of the Global Component of the U.S. Integrated Ocean Observing System.

3.0 Program Initiative

3.1 Overall strategy for addressing deficiencies outlined in the Statement of Need Section. The strategic approach underlying this program plan is as follows:

- Build the long-term ocean component of the observing system in the context of a comprehensive, multi-year, climate program. Improved marine and coastal forecast services will be immediate byproducts.
- Set an initial 2000-2010 timeline for phased implementation (the time line has now been extended to 2012 because of budget realities).
- Establish accountability by defining specific objectives and performance measures.
- Define an "initial observing system design" that will accomplish the objectives and performance measures. Identify annual milestones to complete the initial system over the time line. Emphasize that the initial design is our best guess at this time – it must be evolutionary as knowledge and technology advance.
- State the obvious – a global observing system cannot be built with existing budgets. Estimate the annual funding needed to achieve the identified milestones. Estimate that NOAA will implement about 50% of the global system.
- Work with national and international partners to achieve 100% completion.

Although NOAA's marine and coastal services and the mission services of the other agencies and nations will benefit from this plan, and are considered throughout, accomplishing NOAA's climate mission is the fundamental driver. The scientific foundations come from the Climate Variability and Predictability program and the Global Carbon Cycle program. The programmatic drivers come from the Climate Observations and Analysis Program, the Climate Predictions and Projections Program, the Climate Forcing Program, and the Climate & Ecosystems Program. It is not the intent of the plan to provide all of the observations needed by these programs but to provide a baseline observing system, to be sustained over the long term, that can be built upon where needed to answer specific questions. This baseline system looks for efficiencies to be gained by utilizing common platforms/sites/data infrastructure for several objectives in parallel, and seeks to foster a system approach to effective international organization of complementary in situ, satellite, data, and modeling components of climate observation.

Priorities for implementation are now in place based on the concept of extending the building blocks that have already been put in place, and on the international GCOS Implementation Plan (GCOS-92) which has been specified as the ocean baseline for GEOSS. NOAA will work to implement the specific actions called for in GCOS-92, particularly those actions assigned to the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). JCOMM is NOAA's principal intergovernmental linkage to international implementation.

3.1.1 NOAA context*:* This plan supports NOAA's strategic goal to monitor and observe: "NOAA will invest in needed climate quality observations and encourage other national and international investments to provide a comprehensive observing system in support of climate assessments and forecasts." The plan details how NOAA will achieve one element of that strategic goal – implementation of the sustained *in situ* ocean component of the global climate observing system – and this plan details how NOAA will implement the Global Component of the NOAA IOOS Major Project.

3.1.2 Interagency context: The observational objectives of NOAA's climate program and those of the CCSP are essentially identical and the ocean observing system architecture detailed below will be implemented by NOAA within the framework of, and as an element of, the CCSP. At the same time the observing system must be advanced in support of climate services, it must also be advanced in response to a national demand for the ocean agencies to coordinate implementation of an U.S. contribution to the Global Ocean Observing System. It is recognized that an effective global ocean observing system can be achieved only through continuing interaction among all national (and international) partners. In this context, NOAA will provide a significant contribution to the Global Component of the Integrated Ocean Observing System (IOOS). Implementation will be coordinated with the National Oceanographic Partnership Program agencies.

3.1.3 International context: The observational component of climate services has by far the greatest opportunity and necessity for international collaboration. A global observing system by definition crosses international boundaries and the potential exists for both benefits and responsibilities to be shared by many nations. The system described below is based on the international design of, and is an U.S. contribution to GCOS-92. The observing system projects that make up the climate component have been developed, and will continued to be evolved, organized and managed, in cooperation with the international implementation panels of the Joint IOC/WMO Technical Commission for Oceanography and Marine Meteorology (JCOMM), and with scientific guidance from the GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC).

3.2 Cost and schedule for each investment

3.2.1 Cost Methodology: Cost estimates are derived by observing platform (buoy, float, shipboard system, tide gauge station, etc.) times the number of platforms maintained per year based on the cost of procuring hardware and software, calibrating sensors, deploying/installing sensors, providing satellite transmission of real time data, quality control and archival of processed data. Due to the harsh environment, most ocean platforms are considered expendables, not capital equipment. Continual purchase of replacement sensors, rebuilding, and reseeding of the arrays are required such that annual maintenance costs in the out years are estimated to be the same as the initial cost of establishing a new platform/system in the first year. For analysis work, the annual cost is mostly intellectual resources (people).

The implementation of the global ocean observing system is based on partnerships. On average, NOAA provides about half of the global requirement, with partner agencies in the U.S., primarily NSF, and partner countries (presently 64 other countries) providing the other half. For some systems, e.g., drifting buoys, NOAA provides more than half, and for some systems, e.g., tide gauge stations, NOAA provides less than half. But system-wide, we estimate half. This is based on historical partnerships over the past 10 years. A report of contributions by countries is maintained at www.jcommops.org/network_status.

Accounting within the ocean program is by "project." Each project files an annual report documenting progress of the previous fiscal year and outlining the work plan for the coming fiscal year. A budget sheet(s) is part of each project report and details the costs required to sustain the project – personnel, supplies, travel, contracts, etc. Cost estimates are based on these documented expenditures. The project reports are compiled each year into an *Annual Report on the State of the Ocean and the Ocean Observing System for Climate*. Hard copies of the *Annual Report* are available from climate.observation@noaa.gov. An electronic file is available at www.oco.noaa.gov.

3.2.2 Schedule: The summary below is based on the Program Baseline Assessment of the 100% requirement. Detailed cost estimates are updated annually in June as part of the Program Baseline Assessment (PBA) and are documented in the PBA Table2.

The ocean observing system needs to be completed as soon as possible in order to provide the fundamental measurements needed to deliver credible climate forecasts and assessments. The executable gap is limited, however, by NOAA's ability to implement new system expansions with available management and infrastructure capabilities. The maximum budget increase per year that can be accommodated is estimated to be $16.8 million. A steady ramp of $16.8 million increase per year therefore describes the optimum multi-year plan to reach 100% capability. The 100% capability budget is estimated using this optimum multi-year ramp. This summary is based on actually budgets through FY06, the President's budget for FY07, and the executable ramp of $16.8 million per year through FY12. Summary:

	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
System annual operating cost ($ M)	40.7	51.2	53.2	58.6	75.4	92.2	109.0	125.8	141.1

4.0 Program Goal and Objectives

4.1 Goal: The goal of this plan is to build and sustain the ocean component of a global climate observing system that will respond to the long-term observational requirements of the operational forecast centers, international research programs, and major scientific assessments.

4.2 Objectives: The ocean is the memory of the climate system and is second only to the sun in effecting variability in the seasons and long-term climate change. It is estimated that the ocean stores 1000 times more heat than the atmosphere, and 50 times more carbon. Eighty-seven percent of the rain and snow that water our Earth comes directly from the ocean. Changing sea level is one of the most immediate impacts of climate change. Additionally, the key to possible abrupt climate change may lie in deep ocean circulation.

Accordingly, the objectives of the sustained ocean observing system for climate are to:

1) Document long-term trends in sea level change;
2) Document ocean carbon sources and sinks;
3) Document the ocean's storage and global transport of heat and fresh water; and
4) Document the ocean-atmosphere exchange of heat and fresh water.

This implementation plan will provide a composite global ocean observing system of complementary networks that includes: 1) deployment and maintenance of observational platforms and sensors; 2) data delivery and management; and 3) routine delivery of ocean analyses. This end-to-end ocean system will provide the critical "up-front" information needed for climate forecasting, research, and assessments – continuous, long term, climate quality, global data sets and a suite of routinely delivered ocean analyses. At the same time, the system will provide real-time data to serve the needs of NOAA's marine and coastal forecast and warning missions and the needs of the other agencies in accomplishing their missions.

5.0 Performance Measures

In order to achieve the four objectives, the system must accurately measure: 1) sea level to identify changes resulting from climate variability; 2) ocean carbon content every ten years and the air-sea exchange seasonally; 3) sea surface temperature and surface circulation to identify significant patterns of climate variability; 4) sea surface pressure and air-sea exchanges of heat, momentum, and fresh water to identify changes in forcing functions driving ocean conditions and atmospheric conditions; 5) ocean heat and fresh water content and transports to identify where anomalies enter the ocean, how they move and are transformed, and where they re-emerge to interacting with the atmosphere; and identify the essential aspects of thermohaline circulation as well as the subsurface expressions of the patterns of climate variability; and 6) sea ice thickness and concentrations. These parameters represent the specific "outcomes" of the global ocean observing system for climate.

The sampling requirements for these parameters have been documented by international GOOS and GCOS. Table 1 lists the requirements as presented at the international OCEANOBS 99 Conference in

Saint-Raphael, France. It represents the best estimates of the international community at this time.

A summary of the sampling requirements for the global ocean, based largely on OOSDP (1995), but with revisions as appropriate. These are a statement of the required measurement network characteristics, not the characteristics of the derived field. The field estimates must factor in geophysical noise and unsampled signal. Some projections (largely unverified) have been included for GODAE.

Sampling Requirements for the Global Ocean							
Code	**Application**	**Variable**	**Hor. Res.**	**Vert. Res.**	**Time Res.**	**#samples**	**Accuracy**
A	NWP, climate, mesoscale ocean	Remote SST	10 km	-	6 hours	1	0.1-0.3°C
B	Bias correction, trends	*In situ* SST	500 km	-	1 week	25	0.2-0.5°C
C	Climate variability	Sea surface salinity	200 km	-	10 day	1	0.1
D	Climate prediction and variability	Surface wind	2°	-	1-2 day	1-4	0.5-1 m/s in components
E	Mesoscale, coastal	Surface wind	50 km	-	1 day	1	1-2 m/s
F	Climate	Heat flux	2° x 5°	-	month	50	Net: 10 W/m²
G	Climate	Precip.	2° x 5°	-	daily	Several	5 cm/month
H	Climate change trends	Sea level	30-50 gauges + GPS with altimetry, or several 100 gauges + GPS	-	monthly means		1 cm, giving 0.1 mm/yr accuracy trends over 1-2 decades
I	Climate variability	Sea level anomalies	100-200 km	-	10-30 days	~ 10	2 cm
J	Mesoscale variability	Sea level anomalies	25-50 km	-	2 days	1	2-4 cm
K	Climate, short-range prediction	sea ice extent, concentration	~ 30 km	-	1 day	1	10-30 km 2-5%
L	Climate, short-range prediction	sea ice velocity	~ 200 km	-	Daily	1	~ cm/s
M	Climate	sea ice volume, thickness	500 km	-	monthly	1	~ 30 cm
N	Climate	surface pCO_2	25-100 km	-	daily	1	0.2-0.3 μatm
O	ENSO prediction	T(z)	1.5° x 15°	15 m over 500 m	5 days	4	0.2°C
P	Climate variability	T(z)	1.5° x 5°	~ 5 vertical modes	1 month	1	0.2°C
Q	Mesoscale ocean	T(z)	50 km	~ 5 modes	10 days	1	0.2°C
R	Climate	S(z)	large-scale	~ 30 m	monthly	1	0.01
S	Climate, short-range prediction	U(surface)	600 km	-	month	1	2 cm/s
T	Climate model valid.	U(z)	a few places	30 m	monthly means	30	2 cm/s

Table 1. From *The Action Plan for GOOS/GCOS and Sustained Observation for CLIVAR* by Needler et al. -- *OCEANOBS 99*

The Proceedings of OCEANOBS 99 and the final report from the conference, *Observing the Ocean in the 21st Century*, outline implementation strategies for achieving these sampling requirements. Additionally, for documenting sea level variability and change, the implementation strategy is further defined in the *International Sea Level Workshop Report*, 1998; and for documenting ocean carbon sources and sinks the implementation strategy is defined in the *Large Scale CO_2 Observing Plan: In*

Situ Oceans and Atmosphere (LSCOP), 2002. The latter plan is for the United States only, but was developed by U.S. scientists working in collaboration with international partners. The international community met in Paris, January 2003, to advance international implementation of the ocean carbon monitoring system and the results have now been published in the *International Ocean Carbon Coordination Project*. The elements of the plans needed to achieve global coverage with an initial ocean observing system have now been detailed in GCOS-92. These foundation documents are available from the NOAA Office of Climate Observation and are listed in Appendix A.

Based on the requirements in Table 1 and the implementation strategies defined in the foundation documents listed in Appendix A, the system's effectiveness in meeting the objectives will be gauged by the performance measure listed below. The goal is to reduce measurement errors to limits acceptable for documenting climate scale changes in the ocean. The reduction of measurement error depends directly on achieving complete global coverage by the *in situ* networks, in conjunction with continuous satellite missions. The present number of data buoys, floats, ships, and tide gauge stations is not adequate. Global coverage can be achieved only by deploying additional platforms to fill the gaps.

The "outcome" performance measures detailed below will quantitatively demonstrate why 100% global coverage is necessary to adequately document climate variability and change in the ocean. At present, the performance measure for sea surface temperature is the only quantitative outcome measure available. The required accuracy is 0.2 degrees Celsius. The present ocean observing system can deliver only 0.6 degrees accuracy. During 2006 similar performance measures will be developed for tracking the errors in measurement of global sea level change, ocean carbon sources and sinks, and the ocean's heat storage. Together with the present sea surface temperature performance measure, these three new performance measures will provide a quantitative way to evaluate the effectiveness of the ocean observing system for delivering climate outcomes. In the mean time, percent of global coverage is the best way to estimate the requirement for deploying the ocean observing system.

Performance Measures:

5.1 Sea Surface Temperature

- PM short tile: Reduce the error in global measurement of sea surface temperature.
- Indicator: Potential satellite bias error.
- Unit of Measure: Degrees Celsius
- Baseline FY 2003: 0.7 degrees
- FY 2008 target: 0.2 degrees
- FY 2012 target: 0.2 degrees
- Reporting Frequency: quarterly
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson
- Approving Individual: Tom Karl
- State of Development: PM well developed"

Explanation: Sea surface temperature is the single most important ocean variable for determining the carbon, heat, and water cycles. Achieving an acceptable error target of 0.2 degrees as soon as possible is the number one priority of the ocean program. This target can be reached in FY 2008 with the existing budget.

5.2 Sea Level

- PM short tile: Reduce the error in global measurement of sea level change.
- Indicator: Difference between tide gauge measurements and satellite altimeter measurements of sea level trend.
- Unit of Measure: cm/decade

- Baseline FY 2005: 0.72
- FY 2008 target: 0.62
- FY 2010 target: 0.50
- Reporting Frequency: Quarterly
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson
- Approving Individual: Tom Karl
- State of Development: Experimental. Being further developed in FY 2006.

Explanation: This new outcome-based performance measure will provide a quantifiable metric for evaluating the observing system's ability to deliver fundamental climate information.

5.3 Ocean Carbon
- PM short tile: Reduce the error in global measurement of ocean carbon sources and sinks.
- Indicator: TBD
- Unit of Measure: TBD
- Baseline FY 2003: TBD
- FY 2008 target: TBD
- FY 2012 target: TBD
- Reporting Frequency: Quarterly
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson
- Approving Individual: Tom Karl
- State of Development: Being developed in FY 2006.

Explanation: This new outcome-based performance measure will provide a quantifiable metric for evaluating the observing system's ability to deliver fundamental climate information.

5.4 Ocean Heat
- PM short tile: Reduce the error in global measurement of ocean heat storage.
- Indicator: Sampling error.
- Unit of Measure: Joules/m^2x10^7
- Baseline FY 2005: 2.2
- FY 2008 target: 1.0
- FY 2012 target: 0.8
- Reporting Frequency: Quarterly
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson
- Approving Individual: Tom Karl
- State of Development: Experimental. Being further developed in FY 2006.

Explanation: This new outcome-based performance measure will provide a quantifiable metric for evaluating the observing system's ability to deliver fundamental climate information.

5.5 Deploy the global ocean observing system
- PM short tile: Deployed global observing systems.
- Indicator: Number of platforms in sustained service.
- Unit of Measure: Percent of target number needed to achieve global coverage.
- Baseline FY 2003: 45%
- FY 2008 target: 68%
- FY 2012 target: 100%
- Reporting Frequency: Quarterly
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson

- Approving Individual: Tom Karl
- State of Development: PM well developed.

Explanation: The international target year for completion of the global system was 2010. NOAA cannot achieve its contribution to this target because the executable gap is only $16.8 million per year (execution is limited by ability to augment implementation work with existing infrastructure). Consequently the target for completion has been shifted back two years to 2012.

5.6 Number of ocean state variables reported
- PM short tile: Number of ocean climate state variables reported.
- Indicator: Essential climate variables listed in the international GCOS Adequacy Report.
- Unit of Measure: Variables analyzed in the annual State of the Climate reported in BAMS.
- Baseline FY 2003: 1
- FY 2008 target: 10
- FY 2012 target: 12
- Reporting Frequency: Annual
- Source of data: Office of Climate Observation
- Who is the person reporting the PM: Mike Johnson
- Approving Individual: Tom Karl
- State of Development: PM well developed"

Explanation: All climate variables need to be analyzed routinely, with error bars, even before the observing system is completed sufficiently to reduce the measurement errors to acceptable limits. Consequently the target for this PM is to achieve regular reporting as soon as possible -- by 2009.

5.7 Summary: 100% Budget Profile Performance Measures:

Performance Measure & Unit of Measure	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
Reduce the error in global measurement of sea surface temperature (degrees Celsius)	**0.532**	**0.500**	**0.400**	**0.300**	**0.200**	**0.200**	**0.200**	**0.200**
Reduce the error in global measurement of sea level change (cm/decade)	**0.72**	**0.70**	**0.65**	**0.60**	**0.55**	**0.50**	**0.50**	**0.50**
Reduce the error in global measurement of ocean carbon sources and sinks	**TBD**	**TBD**	**TBD**	**TBD**	**TBD**	**TBD**	**TBD**	**TBD**
Reduce the error in global measurement of ocean heat storage (Joules/m^2x10^7)	**2.2**	**2.0**	**1.5**	**1.0**	**0.8**	**0.8**	**0.8**	**0.8**
Deployed global observing systems (percent complete)	**53**	**55**	**63**	**72**	**81**	**89**	**97**	**100**
Number of ocean climate state variables reported	**6**	**6**	**6**	**10**	**12**	**12**	**12**	**12**

5.8 Performance Measure linkages to the Outcomes:

	Outcomes					
Performance Measures	**Sea level**	**Ocean carbon**	**SST, surface currents**	**Air-sea exchange**	**Ocean heat & transport**	**Sea ice**
Reduce the error in global measurement of sea surface temperature		X	X	X	X	X
Reduce the error in global measurement of sea level change	X				X	
Reduce the error in global measurement of ocean carbon sources and sinks		X				
Reduce the error in global measurement of ocean heat storage	X				X	X
Deployed global observing systems (percent complete)	X	X	X	X	X	X
Number of ocean climate state variables reported	X	X	X	X	X	X

5.9 System linkages to the Performance Measures: The following sections indicate network improvements that work toward building the observing system as a whole. The ocean observing system is a composite of complementary networks, each one contributing its unique strengths; most serve multiple purposes. One of the primary goals of NOAA's Office of Climate Observation is to look for efficiencies to be gained by utilizing common platforms/sites/data infrastructure for several objectives in parallel. For these reasons it is difficult to assign the network components specifically to product lines on a one-to-one basis. In general, however, the network tasks described below will contribute to the deliverables as follows:

	Performance Measures					
OUTPUT Capacity	**SST**	**Sea Level**	**Ocean Carbon**	**Ocean Heat**	**System Percent**	**Variables Reported**
Tide Gauge Stations		X			X	
Drifting Buoy Array	X	X	X	X	X	
Tropical Moored Buoy Network	X	X	X	X	X	
Ships of Opportunity	X	X	X	X	X	
Argo Profiling Float Array		X		X	X	
Ocean Reference Stations	X	X	X	X	X	
Ocean Carbon Networks			X	X	X	
Arctic Observing System	X	X		X	X	
Data and Assimilation	X	X	X	X	X	
Analysis and Product Delivery	X	X	X	X	X	X

6.0 Milestones

In order to achieve the Performance Measures, the integrated ocean observing system will be completed according to the following schedule. The schedule is based on the initial design and projections of adequate funding. The milestones will be updated annually to reflect evolution of the design as knowledge and technology advance, and to reflect the realities of funding availability.

	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
System % Complete:	48	55	57	59	72	81	89	97	100

Although individual network priorities are described below, they must all go forward together as a system. For example, the global Argo array of profiling floats is a primary tool for documenting ocean heat content; yet deployment of the floats in the far corners of the ocean cannot be achieved without the ships-of-opportunity and dedicated ship time elements; and the Argo array cannot do its work without global over-flight by continued precision altimeter space missions; the Argo measurements must be continually calibrated by deep ocean measurements from the dedicated ships conducting the global ocean carbon inventory surveys; while the measurements taken by all networks will be rendered effective only through the data and assimilation subsystems.

Priorities and milestones for the individual networks follow. For each network the several priority tasks are listed in tabular form. The bottom lines of the tables give the representative milestones that are shown graphically in Figure 2; representative milestones are used to simplify the graphic depiction of the phased implementation plan illustrated by Figure 2. Relative emphases in completing the several components of the observing system will depend on the relative priorities assigned to the network tasks in the context of the overall requirements of climate services.

6.1 Tide Gauge Network: Tide gauges are necessary for accurately measuring long-term trends in sea level change and for calibration and validation of the measurements from satellite altimeters, which are assimilated into global climate models for predicting climate variability. Many tide stations need to be upgraded with modern technology. Permanent GPS receivers will be installed at a selected subset of stations, leading to a geocentrically located subset expansion from the present 43 GPS sites to 170 sites globally by 2010. These 170 climate reference stations will also be upgraded for real-time reporting, not only for climate monitoring, but also to support marine hazard warning (e.g., tsunami warning). In cooperation with international partners NOAA will maintain a global climate network of 290 tide gauges stations as the Global Sea Level Observing System (GLOSS) core network, including the subset noted above, for validation of satellite retrievals, validation of climate model results, documentation of seasonal to centennial variability in the El Nino Southern Oscillation, Indian Ocean and Asian-Australian monsoons, tropical Atlantic variability, North Atlantic Oscillation, North Pacific variability, high latitude circulation, western boundary currents, and circulation through narrow straits and chokepoints, and in support of navigation and other marine services. This task will contribute to climate services by providing the long term records needed to 1) document sea level change: 2) document heat uptake, transport, and release by the ocean (sea surface height contributes to the measurement of ocean heat content); and 3) document the ocean's overturning circulation (gradients of sea surface height across straights and choke-points are used to calculate large-scale ocean currents).

	NOAA Contributions FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	International Goal
Operational GLOSS stations	24	24	24	24	24	24	24	24	290
GPS installation	14	14	16	26	46	66	76	86	170
Real-time reporting (GCOS)	32	42	55	66	80	85	86	86	170
GPS data processing			X	X	X	X	X	X	X
Technology development					X	X	X	X	X
International real-time reporting	79	91	106	126	148	155	160	170	170

6.2 Drifting Buoy Array: Data sparse regions of the global ocean are a major source of uncertainty in the seasonal forecasts and are also a major uncertainty in the detection of long-term trends in global sea surface temperature, which in turn is an indicator of global change. Data gaps must be filled by surface drifting buoys to reduce these sources of error to acceptable limits. Standard global SST analyses are derived from satellite retrievals, but the satellite measurements must be continuously tuned using surface *in situ* measurements. The scientific design for the global drifting buoy array calls for 1250 buoys to be maintained world wide, spaced approximately 500 km apart in order to adequately tune the satellites measurements. The drifter array also provides the primary source of global ocean surface circulation measurements which are necessary to validate climate and ocean forecast models, and specially equipped "hurricane drifters" are now routinely air-dropped in the path of hurricanes approaching the U.S. coast in order to improved hurricane intensity and landfall predictions. NOAA, together with international partners, will extend the global SST/velocity drifting buoy array to data sparse regions while adding wind, pressure, salinity, and temperature profile measurement capabilities to serve short term forecasting as well as climate research, seasonal forecasting, and assessment of long term trends. This task will support climate services by providing measurements needed to 1) document heat uptake, transport, and release by the ocean; 2) document ocean carbon sources and sinks (sea surface temperature affects the rate of transfer of CO_2 between the ocean and atmosphere; 3) document the air-sea exchange of water and the ocean's overturning circulation, and 4) document sea level change by providing the sea surface atmospheric pressure measurements that are essential for calculating sea surface height from satellite altimeter measurements.

	NOAA Contributions FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	International Goal
Operational buoys	1040	1040	1040	1040	1040	1040	1040	1040	1250
Hurricane Drifters	8	22	30	30	40	40	40	40	40
Add barometers	210	185	240	240	350	350	350	350	700
Add salinity sensors	15	15	60	110	200	300	300	300	300
Technology development			X	X	X	X	X	X	X
International array size	1250	1250	1250	1250	1250	1250	1250	1250	1250

6.3 Tropical Moored Buoy Network: Most of the heat from the sun enters the ocean in the tropical/sub-tropical belt. The advanced understanding of the role of the tropics in forcing mid-latitude weather and climate was learned primarily through the observations of the tropical moored buoy array (TAO/TRITON) in the Pacific. A similar pilot array in the Atlantic basin (PIRATA) now offers the potential of even better understanding, improved forecasts, and improved ability to discern the causes of longer-term changes in the Oceans. In addition to monitoring the air-sea exchange of heat, the moored buoys provide platforms for supporting instrumentation to measure carbon dioxide and rainfall in the tropics. The global tropical moored buoy network will be expanded from 82 to 119 stations by 2010 and will ultimately span all three oceans - Pacific, Atlantic, and Indian Ocean. This task will support climate services by providing both ocean and atmospheric observations to 1) document heat uptake, transport, and release by the ocean; 2) document carbon sources and sinks; and 3) document the air-sea exchange of fresh water.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Operational buoys	55	55	55	65	75	90	90	90	119
Research buoys	17	22	28	14	15	0	0	0	0
Indian Ocean expansion	4	6	10	15	15	15	15	33	33
Atlantic Ocean expansion	3	6	8	9	9	9	9	9	9
Add salinity sensors	10	60	65	65	75	90	90	90	119
Add flux capability to buoys		4	5	5	5	5	5	5	8
Technology development		X	X	X	X	X	X	X	X
International network size	86	91	97	104	115	119	119	119	119

6.4 Ships of Opportunity: The global atmospheric and oceanic data from Ships of Opportunity (SOOP) have been the foundation for understanding long-term changes in marine climate and are essential input to climate and weather forecast models. Improved instrument accuracy, automated reporting, and improved information about how the observations were taken will greatly enhance the quality of these data, reducing both systematic and random errors. NOAA will improve meteorological measurement capabilities on the global SOOP fleet for improved marine weather and climate forecasting in general, and will concentrate on a specific subset of high accuracy SOOP lines to be frequently repeated and sampled at high resolution for systematic upper ocean and atmospheric measurement. This climate-specific subset will build to a designed global network of 51 lines by 2010 and will provide measurements of the upper ocean thermal structure, sea surface temperature and chemistry, and surface meteorology of high accuracy. Additionally, the SOOP fleet is the primary vehicle for deployment of the drifting arrays. This task will support climate services by providing ocean and atmosphere measurements needed to 1) document heat uptake, transport, and release by the ocean; and 2) document ocean carbon sources and sinks (carbon sampling instrumentation is detailed under a separate task below); and 3) document the air-sea exchange of water and the ocean's overturning circulation.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
High resolution lines	12	12	15	18	21	21	21	21	26
Frequently repeated lines	6	6	6	8	8	8	8	8	25
Add flux/salinity HRX	2	2	7	10	15	15	15	15	26
Auto-met package, VOSClim	0	0	20	50	100	200	200	200	200
Technology development				X	X	X	X	X	X
International lines	39	39	42	45	47	51	51	51	51

6.5 Argo array of profiling floats: The heat content of the upper 2000 meters of the world's oceans, and the transfer of that heat to and from the atmosphere, are variables central to the climate system. Global sea level change is directly related to the ocean's heat content – as the ocean's temperature rises the water expands and thus sea level rises. The Argo array of profiling floats is designed to provide essential broad-scale, basin-wide monitoring of the upper ocean heat content. Three thousand floats will be deployed worldwide by 2007. The U.S. contribution is approximately one-half of this international project. Glider technology will replace standard drifting Argo floats in the boundary currents and targeted deep circulation regions. This task will support climate services by providing measurements needed to 1) document heat uptake, transport, and release by the ocean; 2) document global sea level change, and 3) document the air-sea exchange of heat and water and the ocean's overturning circulation.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Operational Argo floats	1140	1500	1500	1500	1500	1400	1400	1400	2800
Operational gliders	0	0	0	0	0	100	100	100	200
Research gliders	3	5	10	20	50	0	0	0	0
Technology development				X	X	X	X	X	X
International array size	2240	3000	3000	3000	3000	3000	3000	3000	3000

6.6 Ocean Reference Stations:

6.6.1 Subtask 1: NOAA, together with international partners, will implement a global network of ocean reference station moorings, expanding from the present six pilot stations to a permanent network of 21 (plus 8 within the tropical moored buoy network) by 2012. NSF's Ocean Observatories Initiative will provide a major piece of the infrastructure needed for this network, establishing high-capability re-locatable moored buoys in remote ocean locations. NOAA will maintain climate instrumentation aboard the NSF-supplied platforms.

6.6.2 Subtask 2: Monitoring the transport within the ocean is a central element of documenting the overturning circulation of fresh water and heat and carbon uptake and release; heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Long-term monitoring of key choke points, such as the Indonesian through-flow, and of boundary currents along the continents, such as the Gulf Stream, must be established to measure the primary routes of ocean heat, carbon, and fresh water transport. Additionally, major boundary currents such as the California Current have a major impact on marine ecosystems; changing climate regimes in the ocean basins are reflected in changing boundary currents which in turn transfer the ocean climate's influence to fisheries and ecosystems.

6.6.3 Subtask 3: Monitoring thermohaline circulation is a central element of documenting the ocean's overturning circulation and a critical need for helping scientists understand the role of the ocean in abrupt climate change. It is essential that the ocean observing system maintain watch at a few control points at critical locations. Key monitoring sites have been identified by an international team of scientists for deployment of long-term subsurface moored arrays and repeated temperature, salinity, and chemical tracer surveys from research vessels. NOAA will focus with Canadian partners on monitoring the Labrador Sea and upstream locations in Davis Strait and the Canadian Arctic Archipelago, while European partners will focus on the eastern north Atlantic. Additionally, to estimate the effect of Antarctic zone water on the global thermohaline circulation, NOAA will maintain time series moorings and repeat sections in the northwestern Weddell Sea, and will establish time series measurements in the Ross Sea. These locations are important to examine the variability of water mass transformation processes as they relate to climate variability in the Southern Ocean.

6.6.4 Summary: These three subtasks will support climate services by providing ocean and atmosphere measurements needed to 1) document heat uptake, transport, and release by the ocean; 2) document ocean carbon sources and sinks (carbon sampling instrumentation is detailed under a separate task below; and 3) document the air-sea exchange of water and the ocean's overturning circulation.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Operational flux moorings	6	6	6	7	9	9	9	9	21
Operational full depth stations	3	3	3	3	5	10	10	10	45
Operational transport stations	2	3	6	6	6	7	7	7	10
Pacific Raingauge (PACRAIN)	28	28	28	28	28	28	28	28	28
S. Hemisphere sections	0	0	0	0	2	3	3	3	3
Technology development		X	X	X	X	X	X	X	X
International reference stations	42	43	46	49	54	60	78	87	87

6.7 Coastal Moorings: Improved near shore measurements from moored buoys are critical to coastal forecasting as well as to linking the deep ocean to regional impacts of climate variability. The boundary currents along continental coastlines are major movers of the ocean's heat and fresh water (e.g., the Gulf Stream). Furthermore, the coastal regions are critical to the study of the role of the ocean in the intensification of storms, which are key to the global atmospheric transport of heat, momentum and water, and are a significant impact of climate on society. Coastal arrays are maintained by many nations making this a "global" network of "coastal" stations. A climate subset of NOAA's existing network will be improved by augmenting and upgrading the instrument suite to provide measurements of the upper ocean as well as the sea surface and surface meteorology. Ten of these moorings will serve as platforms-of-opportunity for the addition of carbon sampling instrumentation. This task will support climate services by providing ocean and atmosphere measurements needed to 1) document heat uptake, transport, and release by the ocean; 2) document ocean carbon sources and sinks (carbon sampling instrumentation is detailed under a separate task below); and 3) document the air-sea exchange of water.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Upgrade w/climate sensors	0	1	5	10	25	45	65	65	105
Technology development	X	X	X	X	X	X	X	X	X
International coastal network	0	1	5	20	50	90	100	105	105

6.8 Ocean Carbon: Understanding the global carbon cycle and the accurate measurement of the regional sources and sinks of carbon are of critical importance to international policy decision making as well as to forecasting long term trends in climate. Projections of long-term global climate change are closely linked to assumptions about feedback effects between the atmosphere, the land, and the ocean. To understand how carbon is cycled through the global climate system, ocean measurements are critical. NOAA will add autonomous carbon dioxide sampling to the moored arrays and the VOS fleet to analyze the seasonal variability in carbon exchange between the ocean and atmosphere, and in cooperation with NSF will implement a program of systematic global ocean surveys that will provide a complete carbon inventory once every ten years. The ships used to conduct the carbon inventory survey sample the complete ocean water column from top to bottom for temperature and salinity – these measurements are essential to calibrate the measurements from the Argo array. This task is coordinated with the Global Carbon Cycle program, is dependent on implementation of the ship lines and moored and drifting arrays, and will support climate services by providing measurements to: 1) document ocean carbon sources and sinks; and 2) document heat uptake, transport, and release by the ocean.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Inventory lines per decade	6	7	7	8	9	10	11	12	37
Time series moorings	5	5	7	9	10	10	10	10	12
Coastal flux moorings	0	1	1	1	6	11	11	11	29
Flux on ships of opportunity	4	4	6	12	12	12	12	12	21
Technology development				X	X	X	X	X	X
International inventory lines	15	17	20	23	28	31	34	37	37

6.9 Integrated Arctic Observing System: Given the sensitivity of the Arctic environment to climate variability and change, it is in this region that early indications of the future progression of climate change are likely to be first detected. A program of sustained observations of this area is being conducted through dedicated and shared ship-based cruises, permanent oceanographic moorings and gliders, supplemented by acquisition and analysis of historical data sets. The long-term goal is to detect climate-driven physical and ecological change, especially due to changes in sea ice extent and duration, and in ocean density and circulation that together may lead to changes in ocean heat transport, productivity, and food web structure. International collaboration is essential for completing this program, especially with Russia and Canada. Ice-tethered buoys and bottom-mounted moorings are deployed to monitor the drift of Arctic sea ice and to determine its thickness. The long-term goal is to provide an accurate record of changes in sea ice thickness that, together with satellite observations of sea ice extent, can provide an estimate of changes in sea ice volume. This information is critical for improvement of global climate models and development of a regional Arctic climate model. This task will support climate services by providing ocean and ice measurements needed to document heat uptake, transport, and release by the ocean.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Arctic pathway moorings	0	0	1	2	3	4	6	8	12
Ice mass balance buoys	3	3	4	5	5	6	8	8	11
ASOF gateway mooring sets	1	1	1	2	2	2	3	4	8
Automated drifting stations	0	0	0	1	2	3	3	3	3
Ice buoys	14	2	5	8	14	20	20	20	40
Hydrographic stations	1	1	2	4	7	9	10	10	16
Bering Sea moorings	1	1	1	1	4	4	6	6	6
Western boundary sections	0	0	0	1	1	1	1	1	1
Western boundary moorings	0	0	0	3	4	4	4	4	4
Ice buoys and stations	24	21	24	24	41	52	54	54	54

6.10 Dedicated Ship Time: Climate Ship time within the UNOLS research fleet for deployment of the moored and drifting arrays, and for deep ocean surveys is an essential component of this initiative. The deep ocean cannot be reached by SOOP and Argo; yet quantification of the carbon and heat content of the entire ocean column is needed to solve the climate equations. In addition to providing the survey and deployment platforms for the autonomous arrays, the research fleet will maintain sensor suites on a small core of vessels as the highest quality calibration points for validation of the other system measurements. Annual requirements for ship time are 54 days in addition to the Ka'imimoana for TAO/TRITON maintenance, 74 days for the carbon inventory, 34 days for PIRATA in addition to the French/Brazilian support (see Subtask 2), 47 days for ocean reference stations growing to 120 days, 60 days for deployment of the drifting arrays in remote regions, and 46 days for thermohaline circulation monitoring growing to 172 days. This task will support climate services by providing multi-use platforms for the ocean and atmosphere measurements needed to 1) document heat uptake, transport, and release by the ocean; 2) document ocean carbon sources and sinks; and 3) document the air-sea exchange of water and the ocean's overturning circulation.

	NOAA Contributions								International Goal
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	
Ka'imimoana	240	240	240	240	240	240	240	240	240
TAO/TRITON additional	45	45	45	45	45	45	45	45	90
PIRATA	0	35	35	35	35	35	35	35	125
Carbon survey	70	70	70	70	70	70	70	70	240
Coastal flux maps	0	0	60	0	60	0	60	0	240
Reference Stations	43	43	43	43	43	43	43	43	480
Deployment of drifting arrays	0	0	20	45	80	120	120	120	120
Thermohaline circulation	26	26	33	33	33	33	85	79	340
Western Boundary Current	30	30	44	24	30	44	24	30	30
Weddell Sea moorings	4	4	4	4	20	20	20	20	20
Arctic hydrographic sections	0	0	50	60	60	60	60	60	120
NOAA total	458	472	496	659	831	882	882	882	
2045									
NOAA contribution	458	472	496	659	831	882	882	882	
1620									

6.11 Satellites:

The initial ocean observing system for climate depends on space based global measurements of 1) sea surface temperature, 2) sea surface height, 3) surface vector winds, 4) ocean color, and 5) sea ice. These satellite contributions are detailed in other NOAA program plans.

6.11.1 Sea surface temperature: Satellite measurements of sea surface temperature are included in NOAA's operational satellite program and the NPOESS program. Satellite data provide high-resolution sea surface temperature data. Both infrared and microwave satellite data are important. Microwave sea surface temperature data have a significant coverage advantage over infrared sea surface temperature data, because microwave data can be retrieved in cloud-covered regions while infrared cannot. However, microwave sea surface temperatures are at a much lower spatial resolution than infrared. In addition microwave sea surface temperatures cannot be obtained within roughly 50 km of land. A combination of both infrared and microwave data are needed because they have different coverage and error properties. Drifting buoy and other *in situ* data are critically important in providing calibration and validation in satellite data as well as providing bias correction of these data. Satellite biases can occur from orbit changes, satellite instrument changes and changes in physical assumptions on the physics of the atmosphere (e.g., through the addition of volcanic aerosols). Thus, drifting buoy and other *in situ* data are needed to correct for any of these changes. This task will support climate services by providing measurements needed to 1) document heat uptake, transport, and release by the ocean; and 2) document ocean carbon sources and sinks (sea surface temperature affects the rate of transfer of CO_2 between the ocean and atmosphere.

6.11.2 Sea surface height: The value of spaced-based altimeter measurements of sea surface height has now been clearly demonstrated by the TOPEX/Poseidon and Jason missions. Changes in sea level during major El Nino events can now be discerned at high resolution and provide realistic model initializations for seasonal climate forecasting. The same data, when calibrated with island tide gauge observations, are also able to monitor the rate of global sea level change with an accuracy of 1 mm per year. The planned NPOESS altimeter will be adequate for shorter term forecasting, but the NPOESS altimeter will not fly in the same orbit as TOPEX/Poseidon and Jason; and for monitoring long-term sea level change, continuation of precision altimeter missions in the TOPEX/Poseidon/Jason orbit is necessary. Jason follow-on altimeter missions (Ocean Surface Topography Mission, OSTM) are necessary to continue the long-term sea level record. NASA and CNES have asked NOAA and EUMETSAT to transition the Jason-class altimeter from research to operations beginning with the OSTM. In FY2006, NOAA will assume primary U.S. responsibility for continuing this international effort. This task will contribute to climate services by providing the long term records needed to 1) document sea level change; 2) document heat uptake, transport, and release by the ocean; and 3) document the ocean's overturning circulation (sea surface height contributes to the measurement of ocean heat and fresh water content and their transport).

6.11.3 Surface vector winds, ocean color, and sea ice: The best methods of sustaining satellite measurement of surface vector winds, ocean color, and sea ice are still a research and development question; over the next five years NOAA, NASA, and NPOESS will weigh the alternatives and determine the long term strategy for maintenance of these elements.

6.12 Data and Assimilation Subsystems:

6.12.1 Subtask 1 – Long Term Stewardship: The value of the observations does not end with their initial use in detecting and forecasting climate variability. The data must be retained and made available for retrospective analyses to understand long-term climate change, and for designing observing system operations and improvements. NOAA's long history and unique expertise in environmental data management will be applied to the ocean observing system. NOAA also will include the vast holdings of historical ocean observations within the context of the integrated environmental data access and archive system. Support will also be provided for a World Ocean Database to incorporate modern data into an integrated profile system.

6.12.2 Subtask 2 – Data Management and Communications: A robust and scalable data management infrastructure is essential to the vision of a sustained ocean observing system. NOAA's ocean climate data element will contribute to the Data Management and Communications System (DMAC) of the U.S. Integrated Ocean Observing System (IOOS) that is being implemented by the National Oceanographic Partnership Program agencies. The DMAC plan integrates data transport, quality control, data assembly, limited product generation, metadata management, data archeology, data archival, data discovery, and administration functions. Uniform access to data will be addressed through the concept of "middleware" connectivity – a common set of standards and protocols that connects all data sources to data users. The middleware approach shields end users from many of the traditional barriers that have been associated with climate data access, including file formats, the distributed location of data, and the large size of some data sets. The preliminary design has been developed by the National Virtual Ocean Data System (NVODS) project.

The nature of IOOS requires the DMAC to be very highly distributed, supporting both large and small data providers at Federal, regional, state, municipal and academic levels. Data assembly centers will be built into the design to add fault-tolerance and increase ease of use. The GODAE server presently at Navy's Fleet Numerical Modeling Operations Center (FNMOC) in Monterey will provide robust, operational access to aggregated and quality-controlled real-time data streams and will be a primary assembly center for NOAA's real-time global measurements. Delayed-mode data sources will be distributed across many institutions including the Asia-Pacific Research Data Center (APDRC) (part of the International Pacific Research Center (IPRC) at the University of Hawaii) and the NOAA Data

Centers. The APDRC will provide data assembly services for delayed-mode observations in a cooperative partnership with the GODAE Server. Historical data set serving is also an important function of the distributed system.

The GODAE experimental period ends in 2007. The GODAE server system is central to the sustained integrated ocean observing system and the server functions that have been developed during GODAE must be continued. The NOPP agencies must be prepared to continue these functions either at Monterey or some other location. The Navy has not expressed interest in long-term support of the GODAE server and NOAA is presently planning to assume the leadership role in sustaining this critical part of the ocean observing system infrastructure.

The Data Management and Communications component of NOAA's ocean climate observing system must also deliver the information products needed by NOAA scientists and managers for decision support. The products must provide the information needed to monitor the month-by-month effectiveness of the observing system and to diagnose problems. The products should include intelligible scientific graphics and human-readable numeric tables that provide an overview of the integrated system, selectively merging the data from all relevant measurement streams. These information products will be a component of NOAA's contribution to IOOS.

6.12.3 Subtask 3 – Four dimensional data assimilation including GODAE: For climate forecasting, the combined fields from many different networks are used as initial conditions to begin the forecast. These combined fields, or analyses, are also used to document what the ocean and atmosphere are doing at present and what they did in the past, thus providing a record of the changing climate. By routinely comparing models and data, shortcomings in the observing system can be identified and both the models and forecasts can be improved. To utilize effectively the ocean observations, NOAA will expand ocean analyses to the global domain and will develop and implement improved assimilation subsystems that can more effectively use the new data types that are being collected. The principal vehicle for developing this capability, involving both national and international communities and producing a variety of marine products in addition to the use of these observations in forecast systems, is the Global Ocean Data Assimilation Experiment (GODAE). The global data and ocean product delivery will be operationalized as a contribution to, and continue as a follow-on to, GODAE through the interagency/international server infrastructure being implemented by GODAE; NOAA will provide the primary U.S. support to sustain the server infrastructure over the long term. In addition to improving initializations for seasonal forecasting at NCEP, NOAA will implement sustained ocean data assimilation activities at GFDL to enable experimental decadal forecasts, provide ocean initial conditions for IPCC type scenarios, monitor ocean heat uptake, monitor the thermohaline circulation for abrupt changes, and develop a capability for monitoring changes in oceanic carbon sources and sinks.

6.12.4 Summary: This task will support climate services by providing the integrating data, synthesis, and analysis infrastructure for the ocean and atmosphere measurements, both *in situ* and space based, needed to: 1) document long-term trends in sea level change; 2) document heat uptake, transport, and release by the ocean; 3) document ocean carbon sources and sinks; and 3) document the air-sea exchange of water and the ocean's overturning circulation.

	NOAA Contributions								International
	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Goal
Data set development	X	X	X	X	X	X	X	X	X
World Ocean Database			X	X	X	X	X	X	X
Standards and protocols			X	X	X	X	X	X	X
Systems interoperability	X	X	X	X	X	X	X	X	X
Automated monitoring tools	X	X	X	X	X	X	X	X	X

IPRC server	X	X	X	X	X	X	X	X	X
GODAE pilot activities (JIMO)	X	X	X	X	X	X	X	X	X
Operationalize GODAE pilot					X	X	X	X	X
Sustain GODAE server			X	X	X	X	X	X	X
Argos data processing	X	X	X	X	X	X	X	X	X

7.0 Management Plan – System organization and product delivery

A global effort of the proposed magnitude must be integrated, organized, and managed as a system in order to be effective. Matrix management is NOAA's corporate business practice and standard protocol. This management plan will follow that protocol by capitalizing on the capabilities that presently exist across the agency while building toward the vision of a single composite system.

Implementation of the individual *in situ* networks will continue to be through distributed centers of expertise at the NOAA Research laboratories, the National Ocean Service Center for Operational Oceanographic Products and Services, the National Data Buoy Center, and the university laboratories that have developed the instruments and techniques. The space components and data management will be centered in the NOAA Environmental Satellite, Data and Information Service. The focal point for developing global ocean data assimilation capabilities will be the Geophysical Fluid Dynamics Laboratory in partnership with the National Centers for Environmental Prediction and university-based applied research centers.

To weld the distributed efforts together into the single vision, NOAA has established the Office of Climate Observation (OCO) under the auspices of the NOAA Climate Program Office. OCO is charged with advancing NOAA's multi-year program plan for *Building a Sustained Ocean Observing System for Climate.* The OCO is a hybrid combining the functions of a traditional program office with the functions of a center for system monitoring, evaluation, integration, and action. The individual network managers will continue to monitor and evaluate the performance of their individual networks, while the OCO will build the capability to monitor and evaluate the performance of the system as a whole, and take action to evolve the *in situ* networks for overall effectiveness and efficiency in meeting climate observation objectives.

The OCO is the management focus for the distributed ocean network operations and, utilizing the NOAA Observing System Architecture, establishes and maintains operational linkages between the networks and NOAA's other *in situ* and satellite elements and the data and modeling activities that are essential components of climate observation. The office provides a central point of contact within NOAA for coordination with the other agencies and nations involved in observing system implementation. The office receives and acts on feedback from the observing system customers - the operational forecast centers, international research programs, and major scientific assessments.

7.1 Subtask 1 – System Monitoring: The OCO monitors the status of the globally distributed networks to anticipate gaps and overlaps in their combined capabilities. Real-time reports from all platforms are being centralized so that up-to-date status can be displayed at all times. The office is working to report system statistics and metrics, routinely and on demand.

7.2 Subtask 2 – Evaluation: An team of expert scientists both internal and external to NOAA is being established to continually evaluate the effectiveness of the networks in meeting the performance measures and the adequacy of the deliverables in meeting the system objectives. The team of experts will evaluate analysis/synthesis products, recommend product improvements, recommend where additional sampling is needed or redundancies are not needed, recommend better utilization of existing and new *in situ* and satellite data, and assess the impacts of proposed changes to the system.

7.3 Subtask 3 – Take action to evolve the *in site* systems: System monitoring and evaluation will be useless unless there is responsive action taken to build the system, fix problems, and improve sampling strategies. Decisions must be made to implement the best solutions to conflicting requirements (multiple partners and customers have differing missions and will inevitably have differing requirements), to re-deploy existing resources to best improve the system, to select the highest priorities for system extensions and funding of new ideas, and to agree on quid pro quo with interagency and international partners. The OCO is charged with advancing NOAA's multi-year program plan and with evolving the system for maximum effectiveness and efficiency along the way.

7.4 Subtask 4 – Intra-agency, Interagency, and International Coordination: National and international coordination is essential to success in building the global ocean observing system for climate. The OCO is charged with building the infrastructure necessary to organize NOAA's ocean observing efforts along three axes – 1) climate services, 2) the U.S. Integrated Ocean Observing System, and 3) international implementation.

1) For climate services the ocean observations must be available to be combined with data from the atmospheric networks, land surface networks, and cryosphere networks. The requirements from the three user communities – the forecast centers, research programs, and scientific assessments – must be received and synthesized into common requirements or prioritized if they do not resolve readily.

2) For the U.S. Integrated Ocean Observing System, NOAA's climate system will make a significant contribution to the global component where like data from the various platforms, *in situ* and space-based, must be combined to form complete fields (e.g., sea surface temperature from ships, drifting and moored buoys, and satellites). NOAA's efforts must be combined with the efforts of the other NOPP agencies into a seamless system.

3) For international implementation NOAA must work with the implementation panels of the Joint IOC/WMO Commission for Oceanography and Marine Meteorology (JCOMM) to ensure that consistent standards and formats are used by all participating nations so that data can be easily shared and that consistent quality can be expected from all platforms regardless of their national origin.

In addition to dedicated infrastructure needed for NOAA to operate an office for climate observation, dedicated infrastructure is also needed for operation of the interagency and intergovernmental planning and implementation coordination organizations. These interagency/international organizations rely on funding from the member agencies for their support. NOAA has historically provided a significant portion of the funding needed to maintain the existing international secretariats, science and implementation panels, and capacity building efforts of GOOS, GCOS, and the JCOMM. This funding support has been ad hock and in general from the research programs. As a central component of sustaining the long-term, operational global climate observing system, support for the national/international coordination/implementation infrastructure will be institutionalized via the OCO.

7.5 Subtask 5 – Annual Report on the Ocean's Role in Climate: The organizing framework to bring the multiple elements of the composite ocean observing system together is the routine delivery of an *Annual Report on the State of the Ocean and the Ocean Observing System for Climate*. The National Climate Change Science Program strategic plan has identified the critical need for regular reports documenting the present state of the climate system components. NOAA's Office of Climate Observation is leading the national effort to develop this reporting for the ocean component. The theme of the report is the CCSP overarching question for guiding climate observations and monitoring- "What is the current state of the climate, how does it compare with the past, and how can observations be improved to better initialize and validate models for prediction or long term projections?"

The annual report synthesizes satellite and *in situ* observations integrated with models and provides the products to decision makers, the science community, and the public. This reporting framework also establishes a formal mechanism for implementing a "user-driven" observing system and for reporting on the system's performance in meeting the requirements of the operational forecast centers, international research programs, and major scientific assessments. Stakeholders are invited to provide formal recommendations for system improvement and evolution as part of the annual report process.

The annual report contains four chapters:

Chapter One describes The Role of the Ocean in Climate and includes a description of ENSO, SST, sea ice, and sea level, and the various demands on the system incorporating seasonal, interannual, decadal, and climate change time scales. This chapter sets the context for the report and outlines common themes, including the significance of the global ocean observing system and the demands on the system.

The second chapter documents the State of the Ocean. The target audience is decision makers and non-scientists. This chapter is written by the experts in the field and is an annually updated climatology of the ocean, placed in historical context, with discussion of the present uncertainties and with pointers to products of greater detail and climate applications.

The third chapter documents the State of the Observing System. The target audience is NOAA management. This chapter has two sections:

a) System Progress in meeting milestones is documented by the network managers for their projects and by the OCO for the system in total. Annual statistics and status are given.
b) Work plans for the next fiscal year include future efforts.

Chapter Four recaps the State of the Science. The target audience is scientists. The final chapter of the report contains a bibliography of refereed publications from scientific journals treating the global observation of ocean heat, carbon, fresh water, and sea level change. Each year a selected number of abstracts of particularly relevant scientific papers are published with the report.

7.6 Subtask 6 – External Review: The execution of this plan will be subject to normal management review in accordance with NOAA's Requirements-Based Management Process. Additionally, for specific programmatic advice and guidance, the Climate Observing System Council (COSC) has been established to review the program's contribution to the international Global Climate Observing System and to recommend effective ways for the program to respond to the long-term observational needs of the operational forecast centers, international research programs, and major scientific assessments. The Council is comprised of members both internal and external to NOAA who individually offer their expert advice; the Council is not expected to develop consensus opinions. The term of membership is two years with a renewal option for two additional terms. The Council meets at least annually to:

- Advise the OCO on priorities for sustaining and enhancing components of the global climate observing system.
- Review the accomplishments and future plans of specific program activities.
- Recommend realignment of activities, or entirely new activities, within the program as appropriate to satisfy the evolving requirements for climate observation.
- Bring to the OCO a broad view on national and international climate research and operational activities and their implications.
- Provide coordinating linkages with national and international programs requiring and/or contributing to the implementation of the global climate observing system.
- Advise the OCO on the balance of activities within the program in the context of NOAA's overarching climate service requirements, of other national and international requirements, and of other national and international contributions to the global climate observing system.

7.7 System management and product delivery milestones:

	NOAA Contributions FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	International Goal
System Monitoring	X	X	X	X	X	X	X	X	X
System Evaluation:									
Sea level change		X	X	X	X	X	X	X	X
Carbon sources and sinks		X	X	X	X	X	X	X	X
Air-sea exchange,heat/water	X	X	X	X	X	X	X	X	X
Heat storage/circulation		X	X	X	X	X	X	X	X
Interagency/International panels	X	X	X	X	X	X	X	X	X
International capacity building				X	X	X	X	X	X
Mgmt, wkshps & science mtgs	X	X	X	X	X	X	X	X	X
Mgmt, administration & finance	X	X	X	X	X	X	X	X	
Annual Report	X	X	X	X	X	X	X	X	
External review	X	X	X	X	X	X	X	X	

7.8 Education:

The NOAA Office of Climate Observation sponsors two educational initiatives:

1) Teacher at Sea Program – OCO sponsors one or two teachers each year to participate in ocean observing system research and implementation on board NOAA and other research vessels.

2) Adopt a Drifter Program – OCO established this program in December 2004 to enable K-16 teachers and their students to adopt a drifting buoy by partnering with an international school. They can follow their buoy's movement across the ocean by using OCO's Adopt a Drifter website.

Appendix A

Foundation Documents

Observing the Oceans in the 21st Century, edited by Chester J. Koblinsky and Neville R. Smith, 2001, GODAE Project Office, Bureau of Meteorology, Melbourne, Australia, ISBN 0642 70618 2.

OCEANOBS 99, proceedings of the International Conference on the Ocean Observing System for Climate, GCOS/GOOS/WCRP Ocean Observations Panel for Climate and the CLIVAR Upper Ocean Panel, Saint-Raphael, France, October 1999.

International Sea Level Workshop Report, GCOS/GOOS/WCRP Ocean Observations Panel for Climate and the CLIVAR Upper Ocean Panel, April 1998, GCOS #43, GOOS #55, ICPO #16.

A Large Scale CO_2 Observing Plan: In Situ Oceans and Atmosphere (LSCOP), a contribution to the implementation of the U.S. Carbon Cycle Science Plan by the *In situ* Large-Scale CO_2 Observations Working Group, April 2002.

Implementation Plan for the Global Observing System for Climate in support of the UNFCCC (GCOS-92), the Global Climate Observing System, October 2004, GCOS #92, WMO/TD #1219.

CHAPTER 1

The role of the oceans in climate

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1. Introduction

The oceans cover about 71% of the Earth's surface and contain 97% of the Earth's water (see Trenberth 2001). Through their fluid motions, their high heat capacity, and their ecosystems, the oceans play a central role in shaping the Earth's climate and its variability. Changes in sea level have major impacts on coastal regions and storm surges. Accordingly, it is vital to monitor and understand changes in the oceans and their effects on weather and climate, and improve the verisimilitude of model ocean simulations. In this introduction, we outline these aspects and provide a justification for the ocean variables that should be observed (Chapter 2) and the networks and methods (chapter 3) whereby this is achieved.

The most important characteristic of the oceans is that they are wet and, while obvious, this is sometimes overlooked. Water vapor, evaporated from the ocean surface, provides latent heat energy to the atmosphere during the precipitation process. In units of 10^3 km^3 per year, evaporation E over the oceans (436) exceeds precipitation P (399), leaving a net of 37 units of moisture transported onto land as water vapor. On average, this flow must be balanced by a return flow over and beneath the ground through river and stream flows, and subsurface ground water flow. The average precipitation rate over the oceans exceeds that over land by 72% (allowing for the differences in areas), and precipitation exceeds evapotranspiration over land by this same amount (37) (Dai and Trenberth 2002). This flow into the oceans occurs mainly in river mouths and is a substantial factor in the salinity of the oceans, thus affecting ocean density and currents. A simple calculation of the volume of the oceans of about 1330×10^6 km^3 and the through-flow fluxes of E and P implies an average residence time of water in the ocean of over 3,000 years.

Changes in phase of water, from ice to liquid to water vapor, affect the storage of heat. However, even ignoring these complexities, many facets of the climate can be deduced simply by considering the heat capacity of the different components of the climate system. The total heat capacity considers the mass involved as well as its capacity for holding heat, as measured by the specific heat of each substance.

The atmosphere does not have much capability to store heat. The heat capacity of the global atmosphere corresponds to that of only a 3.5 m layer of the ocean (see Trenberth and Stepaniak 2004). However, the depth of ocean actively involved in climate is much greater than that. The specific heat of dry land is roughly a factor of 4.5 less than that of sea water (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited by the low thermal conductivity of the land surface; as a result only the top two meters or so of the land typically play an active role in heat storage and release (e.g., as the depth for most of the variations over annual time scales). Accordingly, land plays a much smaller role than the ocean in the storage of heat and in providing a memory for the climate system. Major ice sheets over Antarctica and Greenland have a large mass but, like land, the penetration of heat occurs primarily through conduction so that the mass experiencing temperature changes from year to year is small. Hence, ice sheets and glaciers do not play a strong role in heat capacity, while sea ice is important where it forms. Unlike land, however, ice caps and ice sheets melt, altering sea level albeit fairly slowly.

The seasonal variations in heating penetrate into the ocean through a combination of radiation, convective overturning (in which cooled surface waters sink while warmer more buoyant waters below rise) and mechanical stirring by winds. These processes mix heat through the mixed layer, which, on average, involves about the upper 90 m of ocean. The thermal inertia of a 90 m

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layer can add a delay of about 6 years to the temperature response to an instantaneous change (this time corresponds to an exponential time constant in which there is a 63% response toward a new equilibrium value following an abrupt change). As a result, actual changes in climate tend to be gradual. With its mean depth of about 3800 m, the total ocean would add a delay of 230 years to the response if rapidly mixed. However, mixing is not a rapid process for most of the ocean so that in reality the response depends on the rate of ventilation of water between the well-mixed upper layers of the ocean and the deeper, more isolated layers that are separated by the thermocline (the ocean layer exhibiting a strong vertical temperature gradient). The rate of such mixing is not well established and varies greatly geographically. An overall estimate of the delay in surface temperature response caused by the oceans is 10–100 years. The slowest response should be in high latitudes where deep mixing and convection occur, and the fastest response is expected in the tropics. Consequently, the oceans are a great moderating effect on climate changes.

Wind blowing on the sea surface drives the large-scale ocean circulation in its upper layers. The oceans move heat around through convection and advection (in which the heat is carried by the currents, whether small-scale short-lived eddies or large-scale currents). Hence ocean currents carry heat and salt along with the fresh water around the globe. The oceans therefore store heat, absorbed at the surface, for varying durations and release it in different places; thereby ameliorating temperature changes over nearby land and contributing substantially to variability of climate on many time scales.

The ocean thermohaline circulation (THC), which is the circulation driven by changes in sea water density arising from temperature (thermal) and salt (haline) effects, allows water from the surface to be carried into the deep ocean, where it is isolated from atmospheric influence and hence it may sequester heat for periods of a thousand years or more. The Meridional Overturning Circulation (MOC) involves not only the THC but also wind-driven currents. The oceans also absorb carbon dioxide and other gases and exchange them with the atmosphere in ways that change with ocean circulation and climate change. In addition, it is likely that marine biotic responses to climate change will result in subsequent changes that may have further ramifications, for instance by changing ocean color and penetration of sunlight into the ocean.

2. An example: The annual cycle

In the subtropics, the oceans typically take up in excess of 100 W m^{-2} in the winter months and give it to the atmosphere in summer mostly in the form of evaporation of moisture. This cools the ocean while eventually warming the atmosphere when released as latent heat in precipitation (Trenberth and Stepaniak 2003, 2004). In mid-latitudes, air coming off the ocean is warmer than the land in winter and cooler in summer, giving rise to refreshing sea breezes and moderating temperatures. Regions influenced by the ocean in this way are referred to as having maritime climates.

An example of the role of the oceans in moderating temperature variations is the contrast in the mean annual cycle of surface temperature between the northern hemisphere (NH) (60.7% water) and southern hemisphere (SH) (80.9% water). The amplitude of the 12-month cycle between 40 and 60° latitude ranges from <3°C in the SH to about 12°C in the NH. Similarly, in mid-latitudes from 22.5–67.5° latitude, the average lag in temperature response relative to peak solar radiation is 32.9 days in the NH versus 43.5 days in the SH (Trenberth 1983), reflecting the differences in thermal inertia.

3. The oceans and sea ice

Sea ice is an active component of the climate system and varies greatly in areal extent with the seasons, but only at higher latitudes. In the Arctic where sea ice is confined by the surrounding continents, mean sea ice thickness is 3–4m thick and multi-year ice can be present. Around Antarctica the sea ice is unimpeded and spreads out extensively, but as a result the mean thickness is typically 1–2 m. Sea ice caps the ocean and interferes with ocean-atmosphere exchanges of heat, moisture, and other gases. Melting sea ice freshens the ocean and diminishes the density. However, its greatest impact is through changes in albedo of the surface; the much darker ocean surface absorbs more solar radiation, further warming the ocean and leads to the ice-albedo positive feedback that amplifies initial perturbations. Diminished sea ice also increases moisture fluxes into the atmosphere, which may increase fog and low cloud, adding further complexity to the net albedo change. Ocean currents transport sea ice, which is also subject to stresses from surface wind.

4. Coupled ocean-atmosphere interactions

Understanding the climate system becomes more complex as the components interact. El Niño events are a striking example of a phenomenon that would not occur without interactions between the atmosphere and ocean. El Niño events involve a warming of the surface waters of the tropical Pacific. Ocean warming takes place from the International Dateline to the west coast of South America and results in changes in the local and regional ecology. Historically, El Niño events have occurred about every 3–7 years and alternated with the opposite phases of below average temperatures in the tropical Pacific, dubbed La Niña. In the atmosphere, a pattern of change called the Southern Oscillation is closely linked with these ocean changes, so that scientists refer to the total phenomenon as ENSO. Then El Niño is the warm phase of ENSO and La Niña is the cold phase.

The strong sea surface temperature (SST) gradient from the warm pool in the western tropical Pacific to the cold tongue in the eastern equatorial Pacific is maintained by the westward-flowing trade winds, which drive the surface ocean currents and determine the pattern of upwelling of cold nutrient-rich waters in the east. Because of the Earth's rotation, easterly winds along the equator deflect currents to the right in the NH and to the left in the SH and thus away from the equator, creating upwelling along the equator. Low sea level pressures are set up over the warmer waters while higher pressures occur over the cooler regions in the tropics and subtropics. The moisture-laden winds tend to blow toward low pressure so that the air converges, resulting in organized patterns of heavy rainfall and a large-scale overturning along the equator called the Walker Circulation. Because convection and thunderstorms preferentially occur over warmer waters, the pattern of SSTs determines the distribution of rainfall in the tropics, and this in turn determines the atmospheric heating patterns through the release of latent heat. The heating drives the large-scale monsoonal-type circulations in the tropics, and consequently determines the winds. If the Pacific trade winds relax, the ocean currents and upwelling change, causing temperatures to increase in the east, which decreases the surface pressure and temperature gradients along the equator, and so reduces the winds further. This positive feedback leads to the El Niño warming persisting for a year or so, but the ocean changes also sow the seeds of the event's demise. The changes in the ocean currents and internal waves in the ocean lead to a progression of colder waters from the west that may terminate the El Niño and lead to the cold phase La Niña in the tropical Pacific. The El Niño develops as a coupled ocean–atmosphere phenomenon and, because the amount of warm water in the tropics is redistributed, depleted and restored during an ENSO cycle, a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This means that the future evolution is potentially predictable for several seasons in advance.

5. Sea level

Another major role of oceans in climate that has major impacts on multi-decadal time-scales is sea level rise. Climate models estimate that there is a current radiative imbalance at the top-of-the-atmosphere of about 0.6 to 1 W m^{-2} (Hansen et al. 2005) owing to increases of greenhouse gases, notably carbon dioxide, in the atmosphere. This has increased from a very small imbalance only 40 years ago. Where is this heat going? Some heat melts glaciers and ice, contributing mass to the ocean and thus eustatic sea level rise (Levitus et al. 2001). Levitus et al. (2000) estimated that the heat content of the oceans increased on average by about 0.3 W m^{-2} over the past few decades, but in a somewhat irregular fashion. Hence the main candidate for a heat sink is the oceans, leading to thermal expansion and thus what is known as thermosteric sea level rise (Hansen et al. 2005).

Sea level rose throughout the 20th century by 1.5±0.5 mm/year (IPCC 2001) although this estimate has been increased to 1.8±0.5 mm/year (Church et al. 2004), and about 0.3 mm/year is from isostatic rebound. However, the rate has accelerated from the 1992 to 2005 when accurate global measurements of sea level from TOPEX/Poseidon and Jason altimetry are available (Church et al. 2004), and up-to-date (1993-2005) values average 2.9 mm/year (S. Nerem, personal communication). Nevertheless, controversy remains about longer-term sea level rise (Munk 2003) and there is evidence of bias in the historical sea level station network (Cabanes et al. 2001), although this has been questioned by Miller and Douglas (2004). Whether the recent acceleration is representative and will be sustained or merely reflects the low values near the start of the global record from Mount Pinatubo cooling is not yet clear.

Recently a number of studies have highlighted changes in salinity. Changes in the freshwater balance of the Atlantic Ocean over the past four decades have been revealed by Dickson et al. (2002) and Curry et al. (2003). They find a freshening in the North Atlantic and also south of 25°S, while salinity has increased in the tropics and subtropics, especially in the upper 500

m. The implication is that there have been substantial increases in moisture transport by the atmosphere from the subtropics to higher latitudes, perhaps in association with changes in atmospheric circulation, such as the North Atlantic Oscillation (NAO). If this is the main process of importance then it has small effects on global mean sea level as fresh water is redistributed. However, Antonov et al. (2002) suggest that there is a secular decrease in overall ocean salinity, raising questions about the role of melting glaciers in sea level rise. Wadhams and Munk (2004) suggested that the 20th century eustatic rise is 0.6 mm/yr. Other recent estimates from Meier and Dyurgerov (2002) and Dyurgerov and Maier (2005) for 1992 to 2003 suggest 0.71 mm/yr from glaciers and small ice caps and, with Antarctica and Greenland included (e.g., Krabill et al., 2004), a total of about 0.9 mm/yr. Hence melting of glaciers and ice sheets has added mass to the oceans giving the recent eustatic rise at about 1 mm/yr.

Estimates of other contributions (e.g., Cazenav et al. 2000) find that increased storage of water on land in reservoirs and dams may account for –1.0±0.2 mm/yr and irrigation accounts for another –0.56±0.06 mm/yr, but these are compensated for by ground water mining, urbanization, and deforestation effects, so that the net sum of land effects was estimated as –0.9±0.5 mm/yr.This obviously depends on the time frame and other small contributions also exist. Nevertheless, the net effect of land storage contributions is now thought to be small although decadal variations may be negatively correlated with thermosteric sea level change (Ngo-Duc et al. 2005).

The steric contribution from thermal expansion is based mostly on the analysis of the historical record of Levitus et al. (2000, 2001). Yet that record is based on subsurface ocean measurements which are inadequate in many areas; for instance little or no sampling over many parts of the southern oceans to even determine the mean, let alone the variations with time. Although earlier suggestions that most of the post-1993 sea level rise of 3 mm/year is thermosteric (Cabanes et al. 2001; Cazenave and Nerem 2004) the strong observational evidence for a significant eustatic contribution of order 1 mm/yr during this period suggests that about 2/3 of the increase is thermosteric (Lombard et al., 2005). Other recent estimates for the past decade place only 1.6 mm/year of the total sea level rise as being the thermosteric contribution, corresponding to 0.86±0.2 W m^{-2} into the ocean (Willis et al. 2004), or in terms of energy about 0.6 W m^{-2} globally.

Although there has been a reasonable accounting for the observed changes, considerable uncertainties still exist. Clearly this is one area where sampling by ARGO floats will have an enormous positive impact. Future sea level rise and whether or not the rate is increasing are vital issues for climate change as they can have huge impacts on small island states and coastal regions. Biggest impacts on coastal erosion and flooding occur through combinations of high tide and storm surges on top of the rising sea level.

6. A topical example: hurricanes

The record breaking hurricane season in the North Atlantic in 2005 has highlighted several issues of importance to oceanography. The 2005 season has the largest number of named storms (23), the largest number of hurricanes (13), the only time 3 category 5 storms have occurred, the most intense storm (Wilma, 882 hPa central pressure), the most intense hurricane in the Gulf of Mexico (Rita, 897 hPa), the most damaging hurricane on record (Katrina) and Katrina was the deadliest in the U.S.) since 1928. Observed and potential changes in hurricanes with global warming are discussed in detail in Trenberth (2005), Emanuel (2005) and Webster et al. (2005) who show that intense storms globally are observed to be increasing, in line with theoretical and modeling expectations and, in particular, in ways strongly related to SSTs.

During a tropical storm, strong surface winds not only take heat out of the ocean at rates of order up to about 1200 W m^{-2}, but also mix the ocean through tens to hundreds of meters, cooling the surface and creating a cold wake (e.g., Walker et al., 2005). Hence the tropical storm activity depends critically not only on SSTs but also subsurface temperatures, especially for whether the ocean environment is favorable for the next storm and thus an entire active season. The so-called warm and deep “Loop Current” in the Gulf of Mexico appeared to play key role in the intensification of Ivan (e.g., Walker et al., 2005), Katrina and Rita. Increasing evidence suggests that predicting hurricanes requires an ocean model to allow these feedbacks on hurricanes to be included. However, surface fluxes are highly uncertain for winds over about 20 m s^{-1} especially concerning the role of ocean spray in exchanging heat and moisture between the ocean and atmosphere, and ocean mixing is also uncertain. Moreover, the role of the mixing in the ocean on currents and the thermohaline circulation (Boos et al. 2004) are major unresolved issues that could change our views of how future climate may change, as current climate models do not include these processes.

7. Why are we observing the ocean?

The above describes the critical role of the oceans in climate. Oceans take up heat in the summer half year and release it in winter, playing a major role in moderating climate. The oceans play a crucial role in ENSO. However, the enormous heat capacity of the oceans means that the oceans also play a key role on decadal and longer timescales. The exact role of the oceans in the North Atlantic Oscillation is being explored. Variations in the ocean affect ecosystems, including fisheries, which are of direct importance for food and the economy. It is therefore important to track the changes in ocean heat storage, as well as the uptake and release of heat in the oceans through the surface fluxes. Salinity effects on ocean density are also important but have been poorly measured, although ARGO profiles will help enormously. It is essential to be able to attribute changes in ocean heat content and the mass of the ocean to causes (such as changing atmospheric composition), using models. Climate models suggest that the THC could slow down as global warming progresses owing to warming and freshening of the high latitude ocean, resulting in counter-intuitive regional relative cooling in the North Atlantic region on multi-decadal time-scales. These aspects are dealt with in chapter 2.

It is vital to establish a baseline of the current state of the ocean as a reference for future assessments. Monitoring of the top 500 m of the tropical Pacific Ocean has been established because of ENSO. It is an excellent start. The World Ocean Circulation Experiment (WOCE) has paved the way. Increasing attention will be devoted to measurements of the biogeochemistry of the oceans and especially the carbon cycle, and possible feedbacks on carbon dioxide levels in the atmosphere. Relationships of physical ocean changes to ecosystems and fish stocks will enable improved fishery management. Observing technologies are evolving, and plans are already well underway for an initial ocean observing system, and while substantial progress has been achieved, it has yet to be fully implemented. The observing system must evolve in ways that protects the integrity and continuity of the climate record. Such a system must be linked to comprehensive analysis capabilities of not only the ocean, but also the atmosphere, sea ice, radiation, precipitation, and other ingredients in the climate system. From time to time it is expected that reanalyses of the past ocean and climate record will be desirable as improvements are made in models and data assimilation systems. Tracking the performance of the observing system to ensure that it is meeting needs is another necessary component (Trenberth et al. 2002). With such information, good models will be enabled to make skilful predictions of climate on timescales ranging from weeks, to interannual (ENSO), to decades in a seamless way. However, good ocean observations are also essential for developing better models.

Ongoing assessments are therefore required of the continually changing state of the ocean, as well as our ability to observe it and assess what is going on. It is therefore appropriate for NOAA to carry out an annual assessment of both the state of the ocean and the state of the observing system, examine how well needs are being met, and find timely remedies for inadequacies. It is also vital to ensure that the observations are analyzed, and products generated to begin to address the issues outlined above. This synthesis phase is important for scientists, but it is essential to justify the ongoing costs of the observing system to taxpayers. Indeed, the increased knowledge and benefits in improved decision making will surely greatly exceed the costs.

8. How are we observing the ocean?

It has been a challenge to observe the whole ocean, globally and throughout its depth on the appropriate time scales. The traditional approach of using observations from ships is expensive and inherently limited in spatial and temporal scope. Moored and autonomous drifting buoys have revolutionized the observing system capabilities and made a global system possible. Space based observations of sea level through altimetry, ocean color, surface wind stress through scatterometry and other passive sensing, SST through infrared (skin, clear sky) and microwave (1 cm bulk, all weather) techniques, precipitation through the Tropical Rainfall Measurement Mission (TRMM) using passive and active radar systems have been established but are largely confined to surface variables, so that in situ observations provide an essential complement. Future missions on salinity will expand capabilities. NOAA has been the main agency for routine in situ observations using diverse but complementary networks of systems (Chapter 3) that are designed to take optimal advantage of opportunities for observations at minimal expense. The mix is likely to change over time as technologies become more sophisticated and developed. Consequently synthesis of all the observations in a physical framework (using models) is an essential step in the overall process of determining the state of the ocean, and continuity of record is a major challenge.

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CHAPTER 2

THE STATE OF THE OCEAN

This chapter presents an overview of the current state of knowledge of ocean climate in 2005, placed in historical context. Expert scientists who monitor, observe, and analyze the ocean variables described in this chapter (e.g., sea level, sea surface temperature, ocean carbon, etc.) have produced concise summaries describing what happened during 2005, placing it in the context of what has happened over the course of many years, and discussing why it is important to monitor these ocean variables. The chapter also discusses how the observing system needs to be enhanced to improve ocean analysis and reduce present uncertainties. In presenting these materials, we attempt to address the needs and interests of a broad audience, including decision makers and scientific generalists who are concerned about the role of the ocean in climate.

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The distribution of precipitation anomalies during 2005 indicates a dipole pattern of wet and dry anomalies over the western and eastern tropical Pacific, respectively, in association with the evolution of a weak El Niño during early 2005. Substantial positive precipitation anomalies were observed over the Gulf of Mexico and Caribbean Sea during the second half of 2005, during which the most active tropical storm seasons on record was recorded. In contrast, lower than normal rainfall was observed over the North Atlantic as a result of the below normal winter storm activity in the oceanic storm track. Mean precipitation for 2005, based on the satellite-derived estimates, was 2.840 mm/day, equivalent to a fresh water influx of 1036.6 Kg/m^2.

Energy and momentum exchanges between the atmosphere and the ocean are examined for the Atlantic Ocean hurricane genesis region. In 2005 there were large departures from typical conditions. These atypical conditions are discussed in terms of tropical cyclone genesis during the record 2005 hurricane season.

Surface currents are measured in-situ by an array of 14 primarily tropical moored buoys and a global array of approximately 1250 drifters. Current variations can also be estimated from satellite altimetry. In 2005, westward current anomalies of nearly 20 cm/s were observed in the equatorial Pacific between 120ºW and the dateline, with strong monthly anomalies in the western Pacific associated with equatorial wave passage. In the Atlantic Ocean, the Florida Current and Gulf Stream were close to their long-term climatological strengths.

Coupled ocean-atmosphere models have demonstrated a strong correlation between the meridional overturning circulation (MOC) and climate variability. NOAA has a 20+ year history of making observations of some of the North Atlantic MOC components, however the first basin-wide time-series observations are now being made and a long-term monitoring system is being designed. Results from 2005 indicate little change in the Florida Current compared to the long-term mean of the transport obtained from cable data, and in the ocean interior there is little evidence of meaningful differences from the long-term averages of the limited historical data that exists for comparison.

Upper ocean heat content is important in understanding and predicting climate phenomena such hurricanes, El Nino, and global warming. This quantity is estimated globally from in situ and satellite data for 2005. The results are compared against estimates from 2004, the past decade, and the past 50 years. The widespread deployment of Argo Project floats starting in 2003 greatly reduces uncertainties in global yearly averages of upper ocean heat content. Interannual variability of the seasonal cycle in mixed layer thickness and temperature (thus mixed layer heat content) is discussed in the tropical Atlantic.

The weak El Niño that developed in mid-2004 came to an end in early 2005. Climatic impacts of this event were muted and generally limited to the tropics because of the weakness of the warm sea surface temperature anomalies and the apparent weak coupling between the Pacific Ocean and the overlying atmosphere. Conditions remained near normal across the Pacific until the end of 2005 when trade winds strengthened and sea surface temperatures cooled indicating the onset of a La Niña event.

In the Arctic region, the destabilization of several known relationships between climate indices and Arctic physical system characteristics presents an intriguing and significant puzzle with respect to the contemporary global climate system. Data from satellites and drifting buoys indicate that the circulation of the Arctic Ocean surface layer has been characterized by an anticyclonic regime for the entire 2000-2005 period. Historically, observational data, along with the results of numerical coupled ice-ocean models, provide evidence that during anticyclonic circulation regimes the arctic atmospheric pressure is relatively higher, wind speed is lower, winter temperatures are colder, ocean waters are fresher, sea ice areal coverage is greater, and sea ice is thicker. Contrary to these tendencies, the extent of the sea ice cover continues to diminish, with the summers of 2002-2005 marking a series of extreme ice extent minima.

The ocean plays a major role in the global carbon cycle. Long-term (decadal) changes in ocean carbon inventory are examined by repeating measurements that are made along specific cruise tracks at intervals of 5-15 years. Recent cruises have suggested that the relative role of the Pacific versus the Atlantic storage of CO_2 has changed over the last decade. Shorter-term (daily to inter-annual) changes in ocean carbon uptake are examined with sea-air CO_2 flux estimates from instruments deployed on ships and moorings. The growing surface CO_2 data set also indicates that there is significant inter-annual variability in the sea-air CO_2 flux.

Introduction

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The material used in this chapter to assess the state of the ocean in the past year comes from three general types of observations and inferences. Many of the original observations used were made by instruments that directly sample the ocean in given locations. For example, sea level is measured by tide gauges at coastal locations, sea surface temperatures (SSTs) are measured by thermometers on ships and buoys, and oceanic carbon is measured by analyzing seawater samples acquired from various locations during research cruises. Inferences from remotely sensed observations, generally from earth-orbiting satellites, are also important, for example as an input to the SST product and for precipitation. Finally, mathematical models of various sorts are used quite substantially to make possible spatially and temporally complete descriptions of many of the parameters discussed.

None of the parameters discussed here are measured in truly continuous fashion for the entire ocean. The diversity of observations and inferred products, and the goal of ensuring a complete description of the full global ocean, implies that we face several crucial challenges. The most immediate of these is the need to convert quantities observed at discrete points in space and time into spatially and temporally complete fields of the value of each parameter on a regular grid. This is often accomplished by a straightforward interpolation of the observations at a given time to each of the points on a regular grid, for example by calculating a weighted average, with weights inversely proportional to distance from the target point, of all the nearby observations. This process of constructing a complete field from irregularly distributed observations is referred to (following the practice in meteorological weather prediction) as *analysis*, and the field that results is called an *analysis*, and you will often see this term used in the chapter.

Since information on the pre-existing state of affairs, or from other observations or physical laws governing the parameter can be useful, much more complex methods are sometimes used. Since we are concerned with the global ocean, which is a fluid for which the governing physical laws can be reproduced reasonably well in a mathematical model, methods are often used that use predictions from such a model jointly with observations to produce complete fields, a process call *data assimilation*. The Global Ocean Data Assimilation System (GODAS) is one such method, and products from GODAS are used on occasion by the authors as a reference for comparison with the analyses derived more directly from observations.

This chapter attempts to describe the state of the ocean climate during 2005 (or, in the case of observations with a lengthy lag in retrieving and analyzing observations, what we **knew** in 2005). While descriptions of the actual observations and the analyses derived from them are very helpful for this, it is also valuable to be able to describe the ocean's state in comparison to that of other years, or to some long-term average state. When possible, we do this by computing and displaying the differences between values from 2005 and from the long-term average for the same location and time of year. Such values are referred to as *anomalies*.

Chapter 2 covers 11 topics, which we have clustered into 5 related groups. We begin with sea level and sea surface temperature (SST), both of which relate to relatively well-observed characteristics of the surface of the ocean. Heat fluxes, precipitation, and a discussion of the exceptional variations in Atlantic Ocean hurricanes during 2005 come next, followed by topics related to motion in the ocean, including surface currents and the thermohaline circulation. We continue with heat content variability and El Niño, which is related to changes in the heat content of the tropical Pacific Ocean, and Arctic variability. We conclude with the important topic of the behavior of the ocean as a source or sink for carbon dioxide.

Sea Level

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2005 Sea Level Deviation

Tide gauges have long observed sea level, and these instruments still provide the long-term context for understanding climate variations. Since 1992, however, satellite altimetry has provided global views of the sea surface height field. In this report both data sources are exploited to describe spatial patterns of sea level deviations during 2005, which largely are a result of wind forcing, and to consider recent sea level measurements in the context of short-term (e.g., a decade, or the length of the altimeter record) and long-term(length of multi-decade tide gauge records) trend estimates, which are used as a measure of sea level rise. The altimetry data for the TOPEX/Poseidon/Jason missions are obtained from NASA (http://podaac-www.jpl.nasa.gov/) and were processed at the University of South Florida. Tide gauge data for US stations were collected by NOAA's National Ocean Service (http://tidesandcurrents.noaa.gov/nwlon.html), and data for international stations were obtained from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/).

Sea level deviations for 2005 are computed as the annual mean sea level at each tide gauge and altimeter grid location relative to a longer-term mean (1993-2001, Figure 1). The spatial patterns of the two datasets are remarkably consistent given differences in ocean dynamics at the coast relative to the open ocean, and the different sample periods of the tide gauge (every hour) and altimeter (every 10 days) time series. Coastal sea level effects are apparent, however, notably along the east coast of North America, where coastal tide gauge sea levels were higher than normal whereas nearby ocean values from altimetry were lower than normal. In many instances, the sea level deviations can be linked directly to anomalous surface winds and their associated upper ocean mass transports (Figure 2). A striking example is a cyclonic (counter-clockwise rotating in the northern hemisphere) wind anomaly centered over the North Atlantic. Cyclonic wind patterns tend to force a divergent upper ocean mass transport and a fall in sea level; the opposite is true for anticyclonic patterns. This anomaly corresponds to a weakening of the Bermuda High and, possibly, an associated weakening of the subtropical wind driven ocean circulation. This would account for the lower than average sea level in the open ocean, and the higher tide gauge sea levels along the North American coast that we noted above to be at odds with the open ocean altimetric heights. Anticyclonic winds associated with an enhanced North Pacific High led to high sea levels over much of the

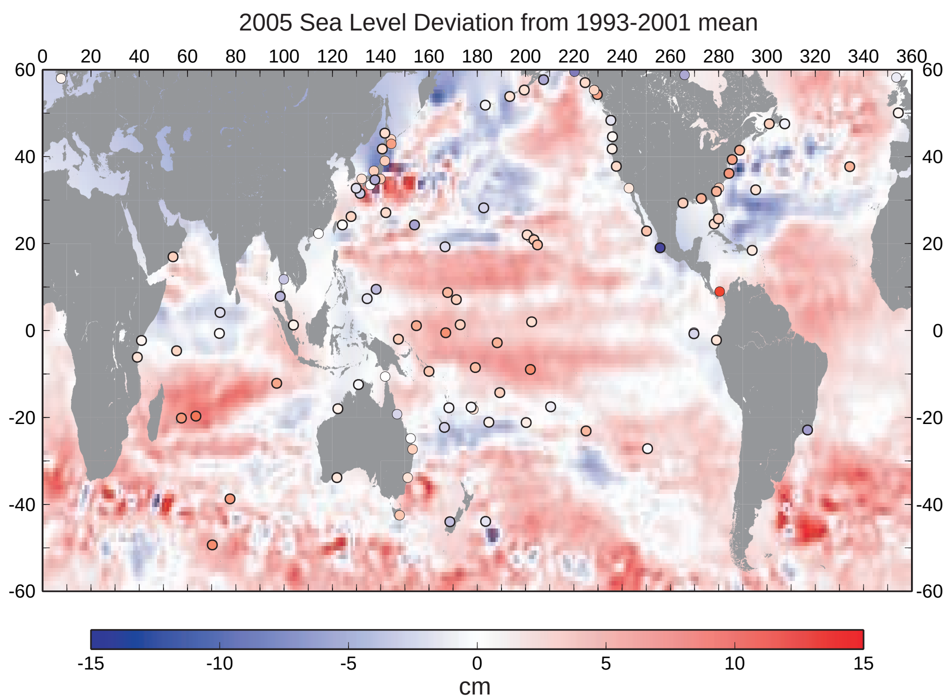

Figure 1. The deviation of 2005 annual average sea level from a 1993-2001 mean, as measured by satellite altimeter (color contour) and tide gauges (circles).

northeast Pacific. Near the equator, increased easterly Trade Winds in the Pacific and Atlantic Oceans led to high sea levels, whereas anomalous westerlies in the Indian Ocean led to low sea levels.

Relative to the previous year, 2005 saw an increase in sea level in the region of the western tropical Pacific north of the equator and east of the Philippines (Figure 3). The pattern developed in response to increased local anticyclonic wind forcing in 2005 relative to 2004. This region is north of the equatorial zone where precursors to El Niño events are often seen in sea level and heat content (Jin, 1997; Meinen and McPhaden, 2000). In general though, 2005 was a year of relatively weak El Niño/La Niña variability (McPhaden, this report, p. 85). This is consistent with the generally weak sea level changes observed along the equator (Figures 2 and 3 compared to the large changes in equatorial sea level that accompany a typical El Niño or La Niña event (Merrifield et al., 1999)). Other major changes in sea level from 2004 to 2005 occurred in the western boundary currents of the North Pacific and Atlantic, again with corresponding changes in the annual wind forcing.

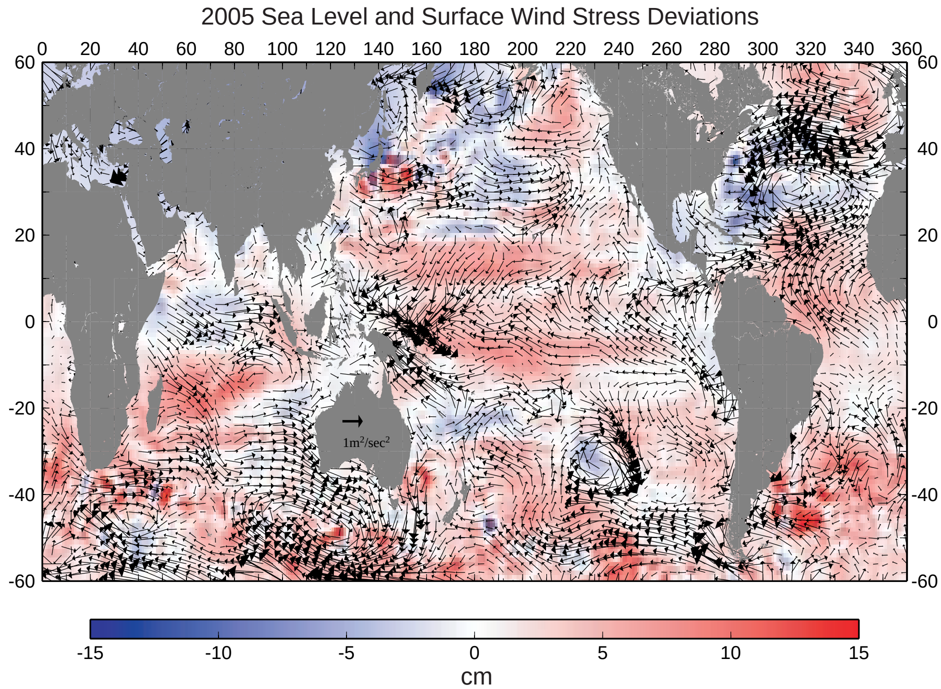

Figure 2. Same as Figure 1, excluding the tide gauge deviations, and including the 2005 deviation of surface winds (data from the National Center for Environmental Prediction).

Global and Regional Sea Level Rise

The deviations shown in Figure 1 were above average over most of the global ocean. Since at least 1993, the time span of Topex/Poseidon/Jason altimeter measurements, global sea levels have been rising at a linear rate of 2.9±0.4 mm/yr (Figure 4, Leuliette et al., 2004; http://sealevel.colorado.edu/; Cazenave and Nerem, 2004). The general increase in globally averaged sea level during 2005 was consistent with this longer trend. At any particular point, however, the rate of sea level change can be very different from the globally averaged rate (Figure 5). A notable example is along the coasts of North America where sea level has fallen in recent years. In the North Pacific, this is presumably associated with a trend in equatorward winds near the coast, which tend to transport surface waters away from the coast (i.e., upwelling favorable). Recent sea level trends appear to be determined by the current polarity of the Pacific Decadal Oscillation (Mantua et al., 1997; Cummins et al., 2005; http://tao.atmos.washington. edu/pdu and it seems likely that the North Pacific sea level trend pattern will reverse sign at some point with a change to rising sea levels near the North American coast.

The primary contribution to the global rise rate (Figure 4) over the past decade is thought to be increased heat content in the upper ocean and the associated increase in volume associated with thermal expansion(Cazenave and Nerem, 2004). Estimates of the heat-related contribution to sea level rise, based on available in situ hydrographic measurements, vary considerably (1.6 +/-0.3 mm/yr, Willis et al. 2004, 1.2 +/- 0.2 mm/yr, Antonov et al., 2005; 2.3 +/-0.8 mm/yr, Carton et al., 2005). Miller and Douglas (2004) conclude that melting ice, resulting in an increase of the mass of the ocean, may account for a larger component of global sea level rise than suggested by the recent estimates of upper ocean heat and volume changes. It is fair to say that there is still considerable uncertainty in specifying the contributions to the global sea level rise budget.

To illustrate how the sea level trends in Figure 5 are highly dependent on record length and residual variability, we examine tide gauge records at locations of recent strong trends in the altimeter data, both for rising (Kwajalein in the western tropical Pacific) and recently falling (San Francisco, CA) sea levels (Figure 6). The recent tide gauge trends (-2.17 mm/yr at San Francisco, 6.64 mm/yr at Kwajalein) are generally consistent with the altimeter derived trends at these locations (Figure 5), even without correcting for land motion at the tide gauges. It is clear that the rates are strongly influenced by recent interannual fluctuations, and that they differ considerably from the longer-term trends estimated over multiple decades (1.95 mm/yr and 1.28 mm/yr, respectively). Zervas (2001) estimates that 50 to 60 year time series are required to obtain a trend with a 1 mm/year confidence interval.

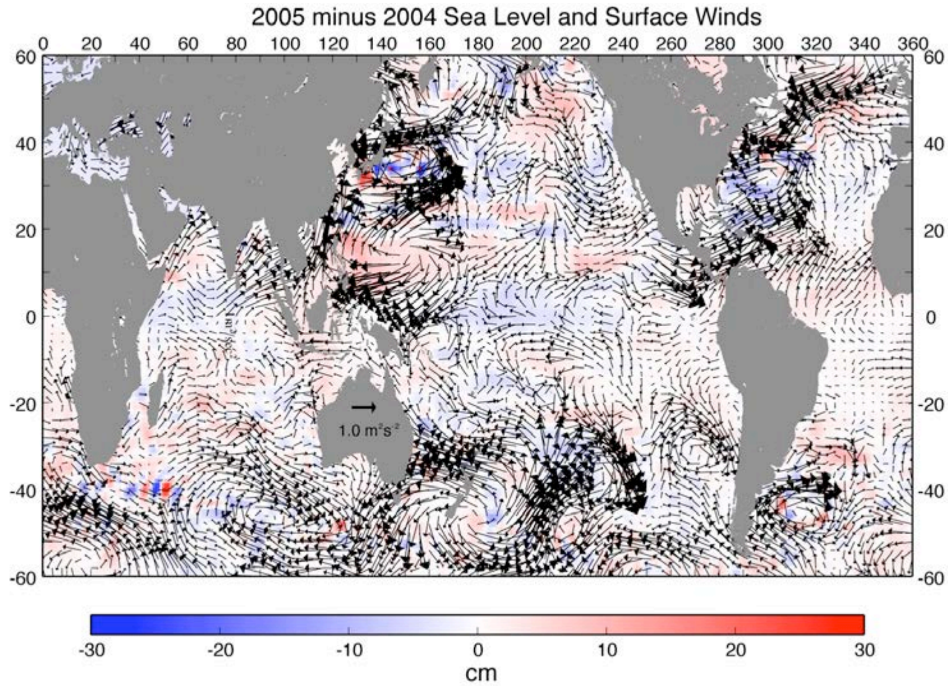

Figure 3. The difference (2005 - 2004) in annual average sea level and surface winds.

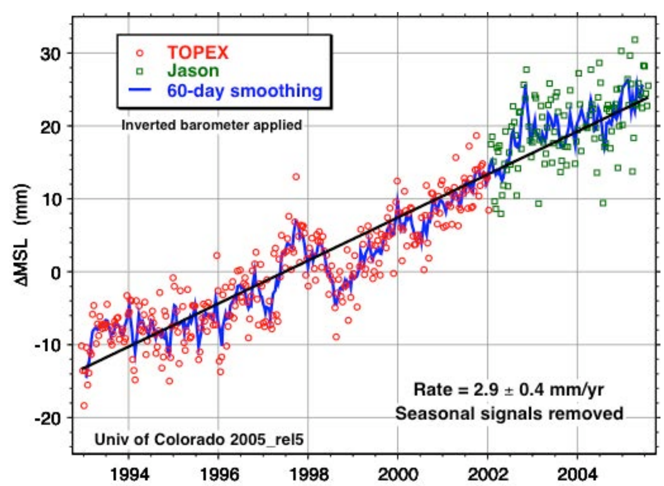

***Figure 4**. Global sea level rise as determined using altimeter measurements from the TOPEX and Jason satellites (source: http://sealevel.colorado.edu).*

New Product Development in 2005

Relative Mean Sea Level Trends

The report of the International Sea Level Workshop (June 10-11, 1997, Honolulu, Hawaii) identified a set of 62 water level stations as a core global network for monitoring long term sea level trends. NOAA National Ocean Service operates and maintains 18 of these proposed climate reference stations and presents routinely-updated analyses of the long-term trends and variability. In support of the program plan objectives of the Office of Climate Observations of NOAA's Climate Program, the sea level trend analysis has been extended to the 44 non-NOS water level stations. The data for these stations were obtained from the Permanent Service for Mean Sea Level (PSMSL, http://www.nbi.ac.uk/psmsl/index.html), the global data bank for long-term sea level information from tide gauges.

Water level records are a combination of the fluctuations of the ocean and the vertical land motion at the location of the station. The sea level variations determined are the linear trend, the average seasonal cycle, and the interannual variability at each station. The trends are available as a table in millimeters/year or feet/century. Sea level trends for these global stations are being incorporated into the NOAA website at http://tidesandcurrents.noaa.gov in the very near future and follow the product look and feel for the U.S. stations on the web at present.

Exceedance Probability Levels

NOAA has developed a new exceedance probability product from the long-term tide station records. Using an Extreme Value General Extreme Value Analysis (GEV) approach (Zervas, 2005) of the monthly observed highest tides, for example at Honolulu, HI (Figure 7a), exceedance probabilities can be expressed as return periods (Figure 7b) and also can be related to various tidal datums (Figure 7c). This product is being completed for long-term NOAA tide stations and eventually for the set of GLOSS reference stations for sea level as well. It will be provided as a web-based product.

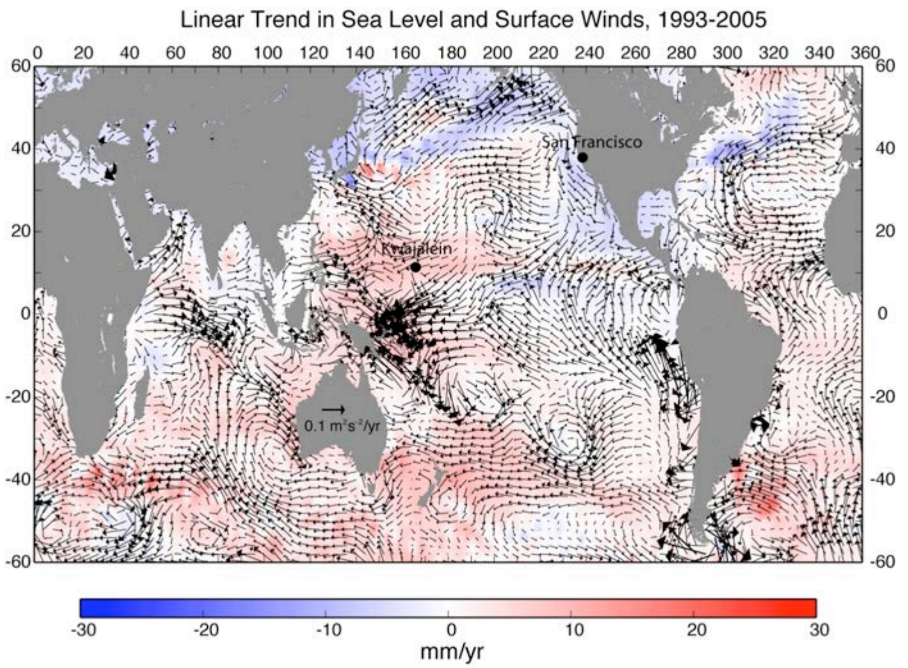

Figure 5. Linear trend in sea level (color contour) and surface winds over the period 1993-2005.

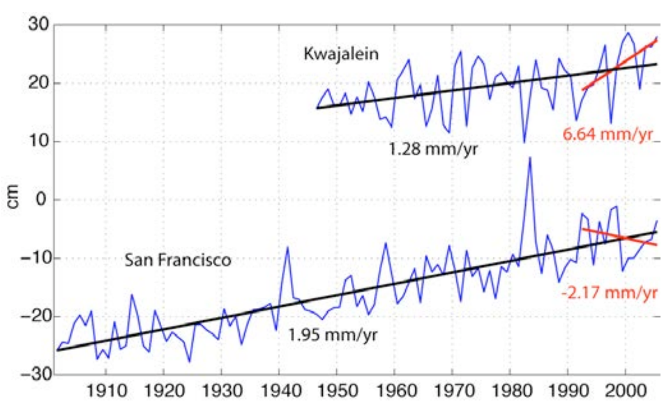

Figure 6. Annual mean sea level from the San Francisco and Kwajalein tide gauges (data courtesy of NOAA-NOS) with estimates of the linear trend for the entire record (in black) and for the time period of the TOPEX and Jason satellite altimeters (in red).

The extreme water level events in 2005 on the east and gulf coasts of the U.S. were dominated by the large number and severity of hurricanes and tropical storms (http://www.nhc.noaa.gov/2005atlan.shtml?). The eastern Pacific also was subject to the effects of several named storms http://www.nhc.noaa.gov/2005epac.shtml?). The severity of the storm surges at many long-term tide station locations redefined the exceedance probability curves when the hurricanes of 2005 were taken into account in the GEV analyses. For instance, the high water levels of Hurricane Katrina

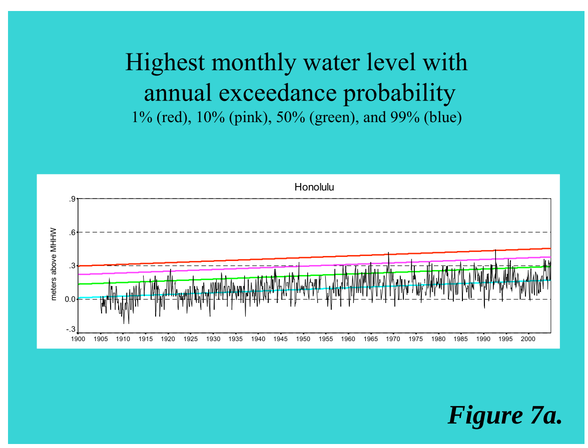

Figure 7a.

raised the 1% exceedance level only slightly at the long-term tide station at Pensacola, FL, but by over one foot at Dauphin Island, AL. Similarly, Hurricane Wilma high water levels at Key West, FL resulted in the

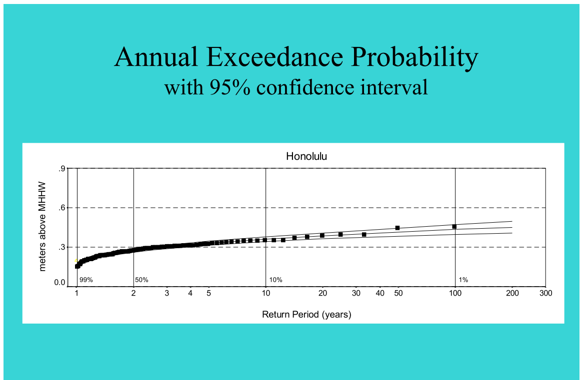

Figure 7b.

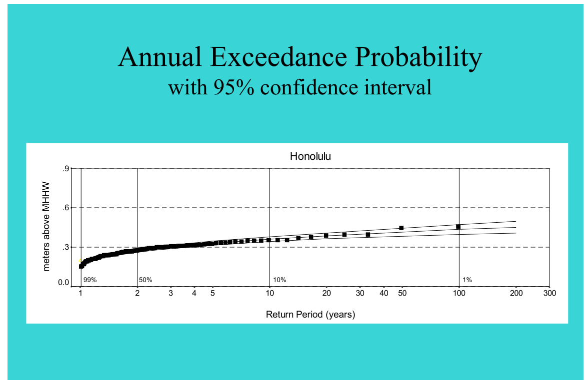

Figure 7c. Extreme Water Level Events in 2005.

1% level being raised slightly. The 1% level can be thought of as representative of the "100-year event" level used in engineering. Figure 8 shows the domi-

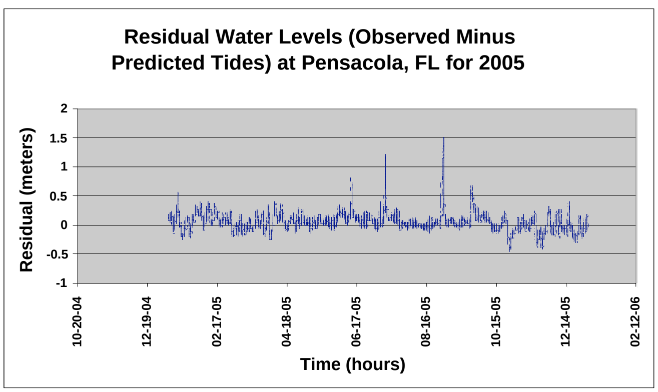

Figure 8. *Atlantic basin example.*

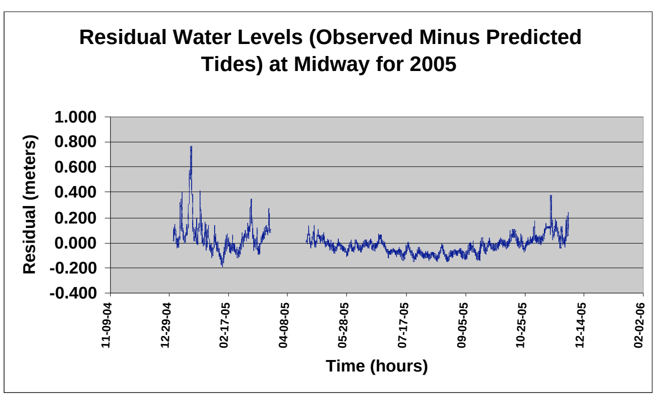

Figure 9. *Pacific basin example.*

nance of the hurricane storm surges in the residual re cord (observed minus predicted tides) for Pensacola, FL. Figure 9 is the residual for a Pacific island station showing a severe water level event in the winter of 2005.

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Sea Surface Temperatures

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Sea surface temperatures (SST) are an important indicator of the state of the earth climate system as well as a key variable in the coupling between the atmosphere and the ocean. Accurate knowledge of SST is essential for climate monitoring, prediction and research. It is also a key surface boundary condition for numerical weather prediction and for other atmospheric simulations using atmospheric general circulation models. In addition, SST is important in gas exchange between the ocean and atmosphere, including the airsea flux of carbon.

The SSTs are obtained from a variety of data sources. The in situ data are obtained from both ships and buoys. The longest data set of SST observations is based on observations made from ships. From 1870 to present, the number of observations generally increased except for noticeable dips during the First and Second World Wars. In addition to the changes in the number of observations, the method of measuring surface marine observations changed over the period from temperatures measured from uninsulated buckets to temperatures measured from insulated buckets and engine intakes. SST observations from drifting and moored buoys became plentiful in the late 1970s. These observations are typically made by thermistor or hull contact sensor and are usually relayed in real-time by satellites. Although the accuracy of the buoy SST observations varies, the accuracies are usually better than 0.5^{o}C, less accurate than the accuracies from ships.

In late 1981, accurate SST retrievals became available from the Advanced Very High Resolution Radiometer (AVHRR) instrument, which has been carried on many NOAA polar orbiting satellites. These retrievals improved the data coverage over that due to in situ observations alone. The satellite retrievals allowed better resolution of small scale features such as Gulf Stream eddies. In addition, especially in the Southern Hemisphere, where in situ data are sparse, SSTs could now be observed on a regular basis in many locations. Because the AVHRR cannot retrieve SSTs in cloud-covered regions, the most important problem in retrieving SST is to identify areas where clouds are present in the view from space, and to eliminate those areas from the data retrievals. After clouds have been eliminated, the SST algorithm is derived to minimize the effects of atmospheric water vapor. The satellite SST retrieval algorithms are "tuned" by regression against quality-controlled buoy data using the multichannel SST technique of McClain et al. (1985). This procedure converts the satellite measurement of the "skin" SST (roughly a micron in depth) to a buoy "bulk" SST (roughly 0.5m). The tuning is done when a new satellite becomes operational or when verification with the buoy data shows increasing errors. During the last decade additional satellite instruments became available. These include Microwave instruments, which can retrieve SSTs even under persistent cloud cover.

The analysis discussed below is produced using AVHRR and ship and buoy data. Figure 1 shows a sample of the daytime and nighttime AVHRR (upper panels) and ship and buoy (lower left panel) SST anomaly data for one week on a 1° grid. Anomalies are defined as differences from a 1971-2002 climatological base period as described by Xue et al. (2003). The white areas in these panels show the regions with missing data. This is especially evident in the panel showing the in situ data. The purpose of an analysis is to produce a complete field on a regular grid. This is done by weighting the different data sources by their relative accuracy and distance from the grid point to be analyzed. The lower right panel, showing the resulting analysis, demonstrates how the satellite and in situ data combine to create a high resolution data set that is more accurate than that derived from satellite retrievals alone. The formal method is formally defined as optimum interpolation (OI) and is as an objective analysis method described in Reynolds et al. (2002). As discussed there, the OI method assumes that the data do not contain long-term biases. Because satellite biases do occur in our period of interest, a preliminary step using Poisson's Equation is carried out to remove satellite biases relative to in situ data before the OI analysis is begun. This method adjusts any large-scale satellite biases and gradients relative to the boundary conditions defined by the in situ field. The satellite data are adjusted by these

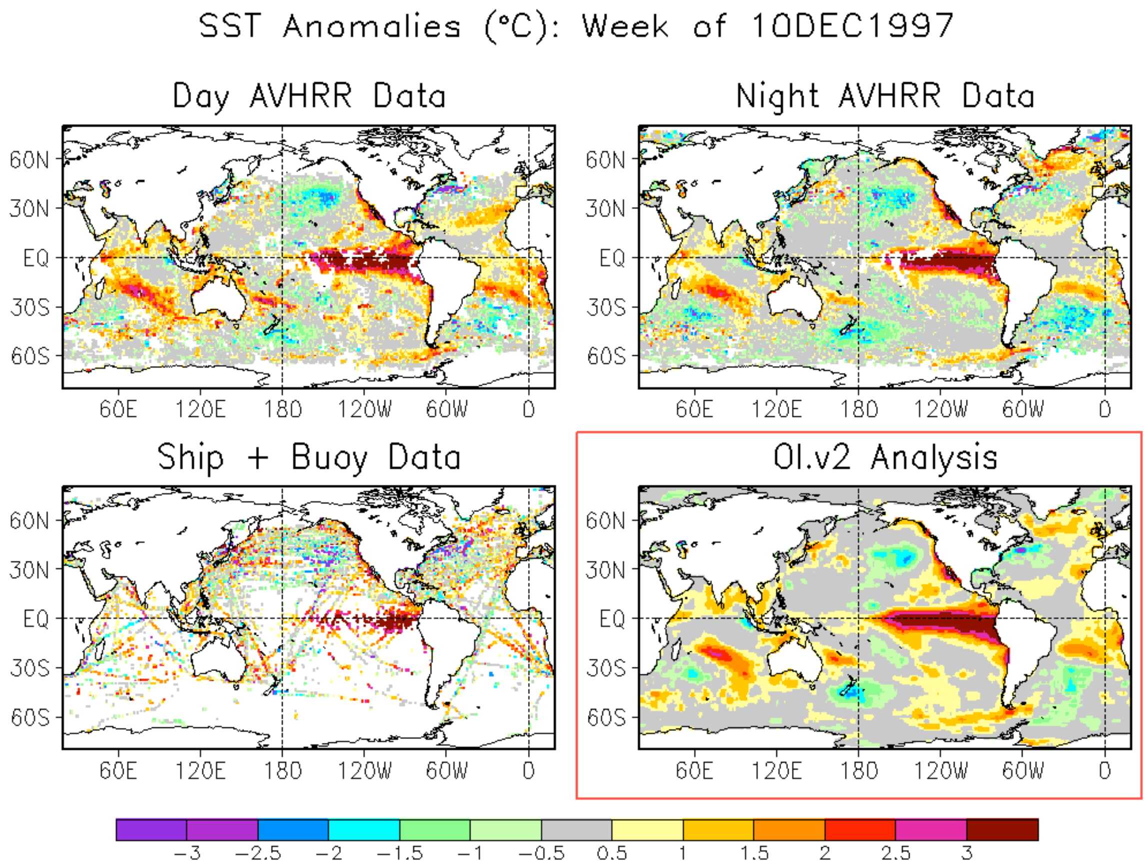

Figure 1. Weekly anomalies on a 1° grid for 10 December 1997. The top two panels the anomalies based on daytime and nighttime AVHRR satellite data, respectively. The left lower panel shows the anomaly based on ship and buoy data. The right lower panel shows the OI analysis using the other panels as input.

smoothed bias corrections before they are used in the OI.

To illustrate the overall changes in 2005, the yearly averages of the monthly anomalies are shown for 2004 and 2005 in Figure 2. The overall impression is that the anomalies are primarily positive. This is due to the overall warming trend of the global SSTs from 1971 to present relative to the mean of the climatological base period. Comparisons of the two years show two important changes: the first in middle latitudes (40°N - 66°N) and the second in the tropical North Atlantic (0° - 30° N). In the middle latitude regions, there is a tendency for the positive anomalies to increase from 2004 to 2005 in the eastern Pacific and western Atlantic. To illustrate the changes with time, monthly anomaly time series are shown for the middle latitude eastern Pacific and western Atlantic in Figure 3. Both regions show an overall warm anomaly over the 1995-2005 period, although the monthly to seasonal variability in the Pacific is less than the Atlantic. There is also evidence of regular summer warming in the Pacific region from 2000 - 2005. This signal is only clearly evident in the Atlantic region in 2003 which is the oceanic response to that summer's European heat wave.

During 2005, there was a record number of strong Atlantic hurricanes. In the recent literature, there has been some discussion to determine if changes in SSTs can imply statistically significant changes in hurricanes (Webster, et al. 2005) or not (Trenberth, 2005). All the reports state that SSTs are not the only variable affecting hurricanes. Because of the changes in the northern tropical Atlantic SSTs from 2004 to 2005, Figure 2, time series are shown for the North Atlantic (10°N - 30°N) and for the Gulf of Mexico in Figure 4. The tropical Atlantic region shows overall warm anomalies with irregular variability on 2 to 5 year periods which is not strongly correlated with the seasonal cycle or ENSO. However, a relatively strong maximum anomaly

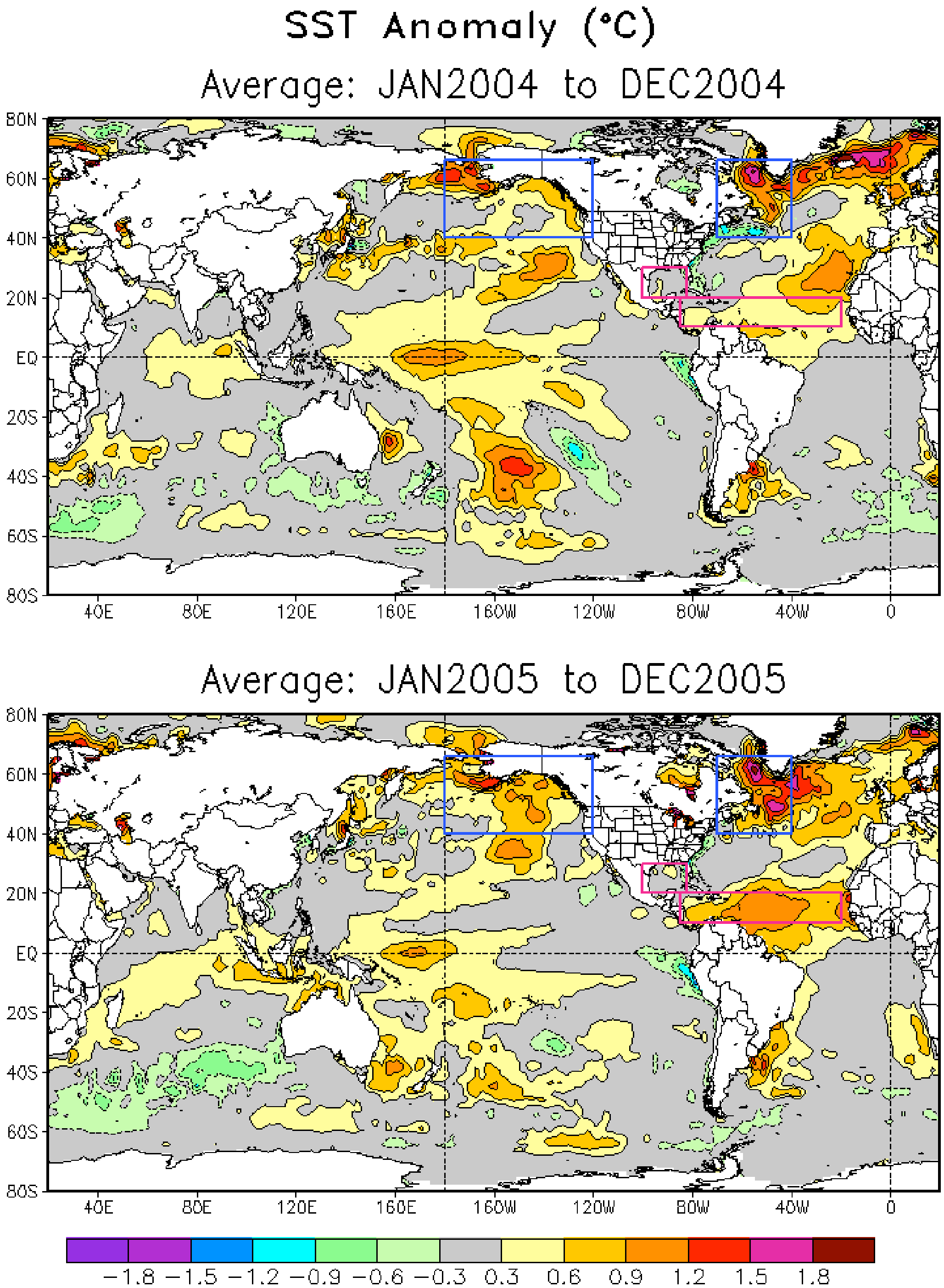

Figure 2. Yearly SST anomalies for 2004 (top) and 2005 (bottom). The anomalies are computed relative to a 1971-2000 base period.

occurs in the summer of 2005. The time series from the Gulf of Mexico appears to be noisier without any no-

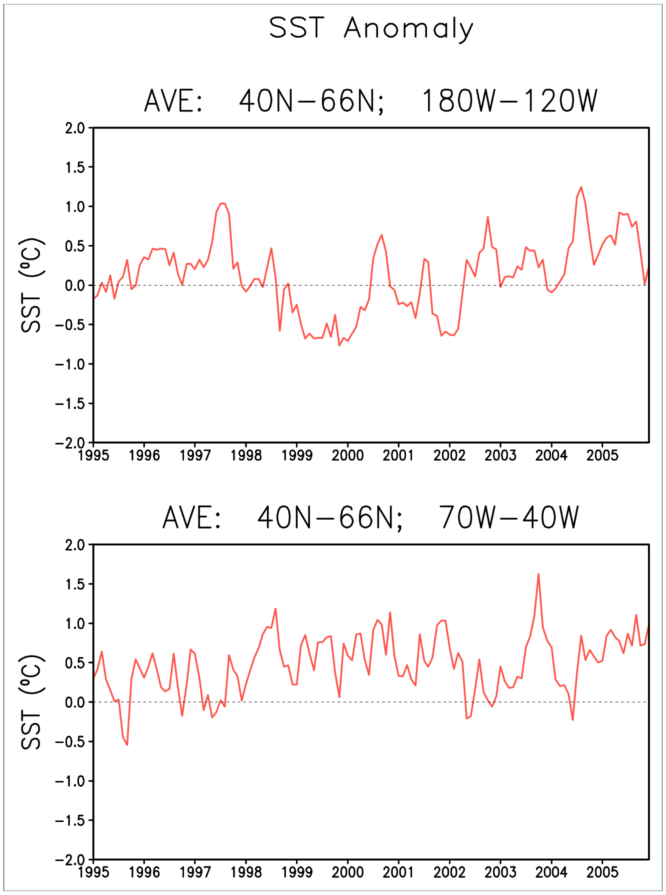

Figure 3. Time series of monthly SST anomalies for the eastern middle latitude North Pacific (top) and the western North Atlantic (bottom). The time series period is January 1995 through December 2005. Regions are indicated in Figure 2.

ticeable signal. To examine the recent summer anomalies in more detail, Figure 5 shows the 2004 and 2005 tropical Atlantic anomalies for July, August and September. In the figure, the 26, 27 and 28°C isotherms of the total SST (anomaly + climatology) are shown for the respective month. Goldberg, et al., (2002) state that local SSTs greater than 26.5°C are needed to generate hurricanes. The figure shows that areas greater than 26.5°C are similar in the corresponding months for 2004 and 2005. However, areas greater than 28°C are larger in July and August 2005 than July and August 2004. As expected, these maps are only of modest help in determining actual hurricane development. However, they are useful background for recent media reports. For example, Time Magazine's October 3, 2005, issue had the bold question on its front cover, "Are we making hurricanes worse?"

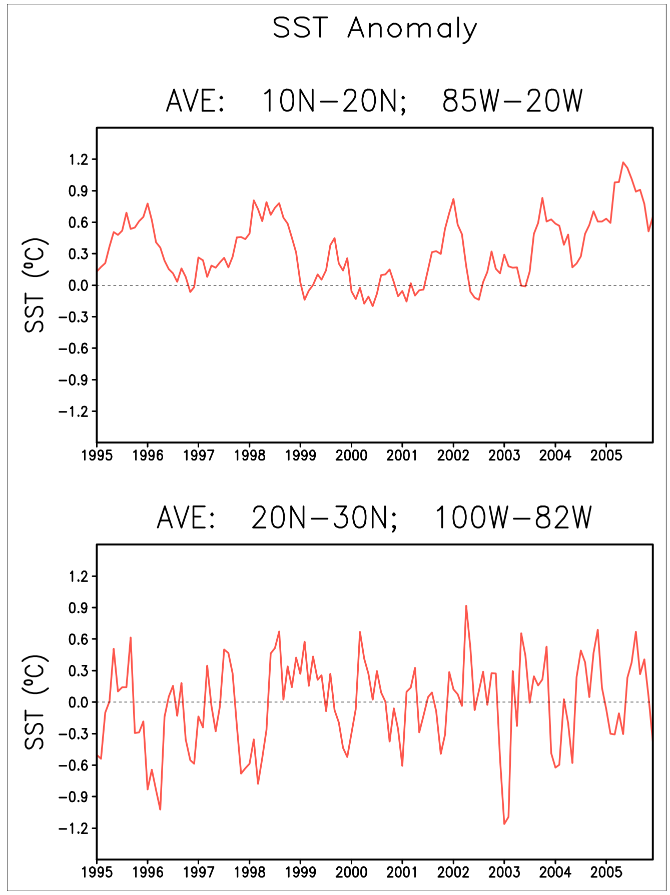

Figure 4. Time series of monthly SST anomalies for the tropical North Atlantic (top panel) and the Gulf of Mexico (bottom panel), otherwise as in Figure 3.

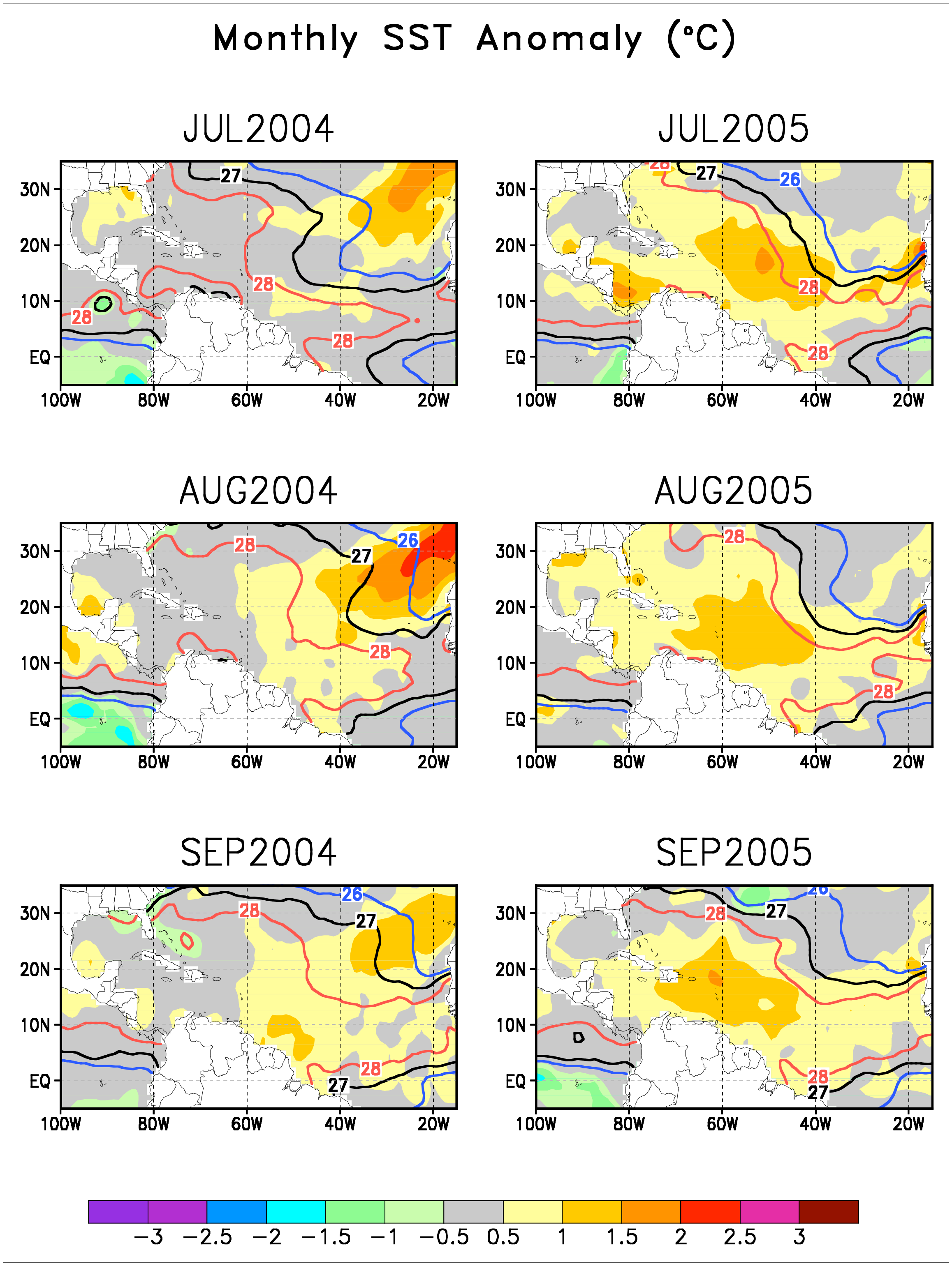

Figure 5. Tropical monthly SST anomalies for July, August and September 2004 (left panels) and for July, August and September 2005 (right panels). Contours show the corresponding monthly total (anomaly + climatology) SST for 26, 27 and 28°C.

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Ocean Heat Fluxes

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Introduction

The oceanic latent heat flux (LHF) is heat energy released by evaporation of sea surface water, and sensible heat flux (SHF) is heat energy transferred by conduction and convection at the air-sea interface. These two fluxes vary with near sea-surface circulation, humidity, and temperature and influence weather and climate processes (Cayan, 1992). Accurate air-sea heat fluxes over the global oceans are required virtually for every aspect of climate studies. For example, air-sea heat fluxes are forcing functions for ocean models that study the generation and distribution of upper ocean temperature anomalies in response to atmospheric forcing. Because ocean influences the atmosphere through sea surface temperature (SST), the relationship between heat fluxes and SST is key to understanding the interaction between the atmosphere and the ocean, and whether such interaction manifests itself in one direction only or in both directions. In the latter case, SST both affects and is affected by heat fluxes; such feedback interaction is called air-sea coupling. The regions where coupled atmosphere-ocean interaction takes place are regions of great climate interest, because any perturbation in SST will lead to changes in the atmospheric circulation and changes in the weather and the climate system. Maps of patterns of air-sea coupling can be derived from coupled atmosphere-ocean models, but, because the models are not error-free, confidence in those patterns rests upon validation with good flux datasets.

However, the structure and variability of the global heat flux fields cannot be obtained from direct observations of fluxes because such direct flux measurements are sparse; instead our knowledge of the global air-sea heat fluxes and their spatial and temporal variability is gained through flux estimates based on bulk parameterizations using basic surface meteorological variables, such as wind speed, temperature, humidity, etc. These variables can be obtained from one of the following three sources: marine surface weather reports from Voluntary Observing Ships (VOS) collected by Comprehensive Ocean-Atmosphere Data Set (COADS), satellite remote sensing, and outputs of numerical weather prediction (NWP) models such as those at the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF). None of the three data sources are perfect, as each of them suffers from at least one of the following four deficiencies: (1) incomplete global coverage, (2) relatively short time series, (3) systematic biases, and (4) random errors. While improving the quality of each data source is essential, our project, the Objectively Analyzed air-sea Fluxes (OAFlux) (Yu and Weller, 2006; the project website http://oaflux.whoi.edu/), shows that we can produce a synthesized flux product with good temporal coverage, improved space and time resolution, and improved quality by combining the advantages in the three surface meteorological data sources using an objective analysis (Yu et al. 2004).

"Objective analysis" is a method for synthesizing measurements/estimates from various sources. The methodology is based on the Gauss – Markov theorem, a standard statistical estimation theory that states, when combining data in a linear fashion, that utilization of a linear least squares estimator is the most efficient process for reducing error in each input data source while producing an estimate that has the minimum variance (Daley, 1991). In the case of our flux analysis, objective analysis allows us to formulate a least-squares problem using available satellite/in situ surface meteorological observations and NWP model outputs to search for a solution that best fits the input datasets. The procedure is applied to each flux-related variable (i.e., wind speed, air and sea surface temperatures, and specific air humidity), from which the fluxes are computed using a bulk flux parameterization (Fairall et al. 2003). In this study, the input datasets are derived from multiple sources, including satellite microwave SST retrievals from TRMM Microwave Imager (TMI) and Advanced Microwave Scanning Radiometer for EOS (AMSR-E) (Chelton and Wentz, 2005), wind speed retrievals from Special Sensor Microwave/Imager (SSM/I) (Wentz, 1992), the weekly optimum interpolation (OI) analyses of Reynolds et al. (2002) (which is described elsewhere in this report), and surface meteorology from the NCEP and ECMWF reanalysis/forecast models. The resulting flux fields have been validated against more than 100 flux buoy measurements acquired by the WHOI Upper Ocean

Processes group (e.g. Moyer and Weller, 1997) and by the PIRATA in the Tropical Atlantic and TAO/TRITON in the equatorial Pacific. These flux fields, produced from the objective analysis, are used below to examine the variability of the global LHF and SHF fields in 2005.

Change of latent and sensible heat fluxes from 2004 to 2005

The 2005 annual mean fields of LHF, SHF, LHF plus SHF over the global oceans (Figure 1) show that large oceanic latent and sensible heat losses occur over the regions associated with three major western boundary currents (WBCs), i.e., the Kuroshio off Japan, the Gulf Stream off the United State, and the Agulhas current off the South Africa. In these regions, near-surface vertical gradients of humidity and temperature are largest and the wind speeds are greatest in the respective hemisphere's fall and winter seasons, and the cold season variability of LHF and SHF dominates the annual mean pattern.

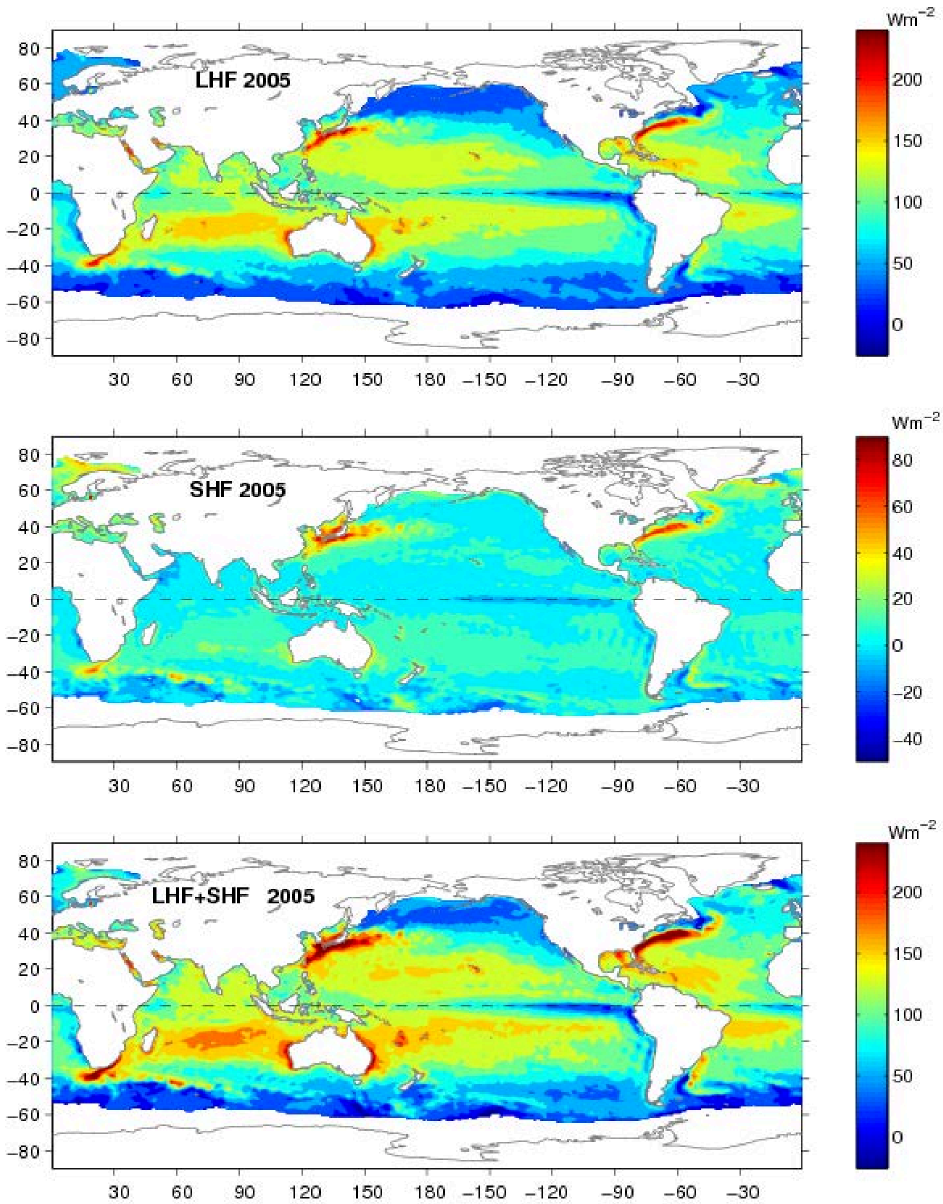

Figure 1 The 2005 annual mean latent heat flux (upper panel), sensible heat flux (mid panel), and latent plus sensible heat flux (bottom panel) in 2005. The sign is defined as upward (downward) positive (negative).

In general, the annual mean SHF has a pattern similar to that of LHF but the magnitude is much smaller. The annual mean LHF plus SHF field reflects primarily the enhanced LHF field. On a year-to-year basis, the three WBC regions are the ocean regions that exhibit greatest variability in LHF and SHF. This is clearly shown from the differences of the 2004 and 2005 annual mean LHF, SHF, and LHF plus SHF (Figure 2). Three additional features are worth noting. First, the anomalies in the difference map of SHF have the same sign as those of LHF in most global basins. Second, the magnitudes of the SHF anomalies are smaller than those of LHF, except for the region of the Kuroshio where the anomalies are both about 40 Wm^{-2}. Finally and most interestingly, the signs of the anomalies associated with different WBC systems are different. For example, the oceanic latent and sensible losses were enhanced (large positive anomalies) from 2004 to 2005 over the Kuroshio region, but reduced (large negative anomalies) over the Gulf Stream region.

Influence of eddy-scale structures is evident in the two-year difference maps. Nevertheless, the change in both LHF and SHF fields from 2004 to 2005 is large-scale: the anomalies are primarily negative over the global basins – suggesting that the oceanic heat loss was overall reduced in 2005.

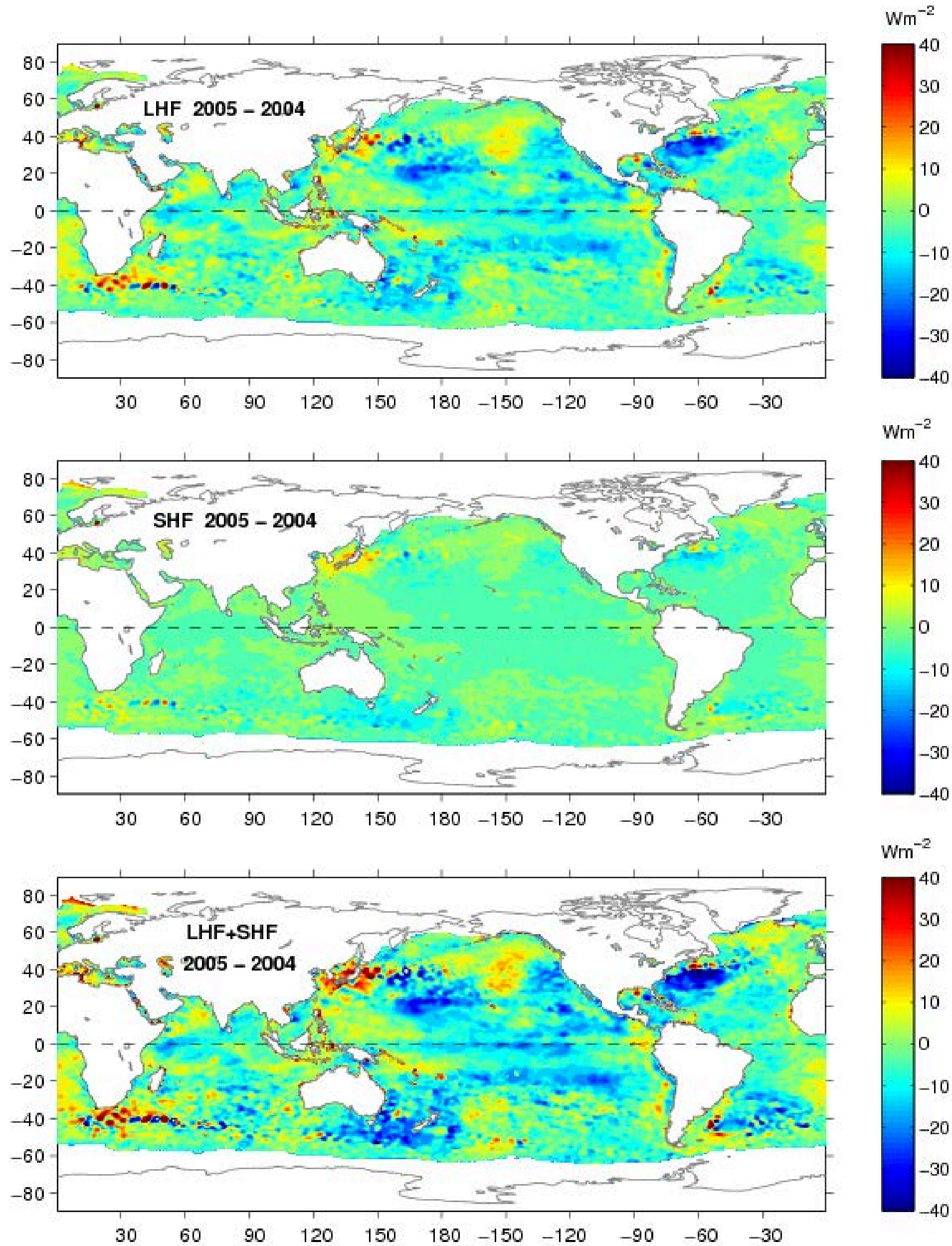

Figure 2 Differences between the 2005 and 2004 annual mean latent heat flux (top panel), sensible heat flux (mid panel), and latent plus sensible heat flux (bottom panel).

Linking the State of Latent and sensible heat fluxes in 2005 with past record

The reduction in the global oceanic heat loss in 2005 is more evident in the plot of year-to-year variations of the annual mean LHF, SHF, LHF plus SHF averaged over the global basins from 1981 to 2005 (Figure 3). The time series is constructed from daily analysis fields produced by the OAFlux project. Over the entire analysis record there is a persistent, long-term increase in the global averaged annual mean LHF, although that trend appears to decrease in recent years. It is not clear yet whether or not the reduction in oceanic heat loss for 2005 is merely a perturbation of the longer term upward trend or an indication of a change in the trend. The latent heat loss, averaged over the global basins, has increased by about 10 Wm^{-2} in the past 20 years. Overall, the change in the total oceanic heat loss, i.e., LHF plus SHF, is dominated by the change in LHF. There is a slight increase in SHF in the 1990s, but the net increase averaged over the global basins is small, less than 2 Wm^{-2}.

Area averages are made for the Kuroshio and Gulf Stream regions (Figure 4) to examine the regional change of LHF and SHF in the past two decades. Clearly, the time series of annual mean LHF plus SHF have a large upward trend in both regions. However, unlike the global averages (Figure 3), the regional averages show strong interannual fluctuations. Unlike the global averages that have a trend starting from the beginning of the analysis record in 1981, the regional averages show a trend toward larger values starting late, in early 1990s. Unlike the trend of the global averages that tends to be flat in recent years, the trend in the two regions is still positive. Furthermore, the slope of the trend in these two regions is twice as great as that of the global averages. Overall, the regional oceanic heat loss has been enhanced by about 20 Wm^{-2} over the past two decades.

Latent evaporation at the air-sea interface results in the transport of energy and water vapor into the atmosphere. The increase of latent heat evaporation in the past 20 years should increase the transport of water vapor into the atmosphere, leading to three questions. First, water vapor is a key element of the hydrological

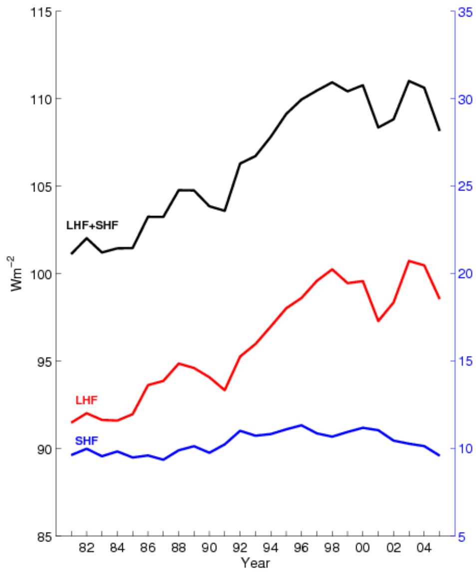

Figure 3 Year-to-year variations of global averaged annual mean latent heat flux (red), sensible heat flux (blue), and latent plus sensible heat flux (black).

cycle, i.e., the cycling of water, in all three phases, within and between the Earth's atmosphere, oceans, and continents. The movement of water vapor in the hydrological cycle is coupled to precipitation and soil moisture. Globally, 86% of evaporation and 78% of precipitation occur over the oceans. How much has the global precipitation, both over the oceans and over the continents, been impacted by the increased evaporation over

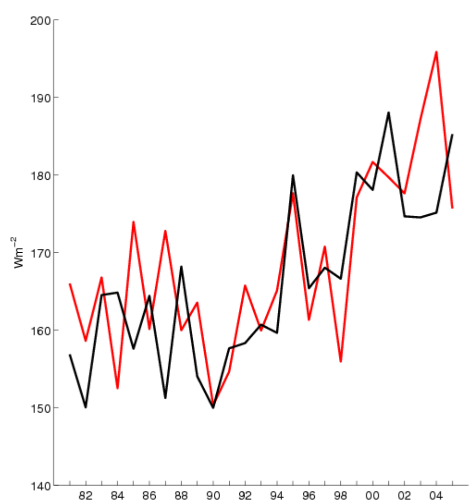

Figure 4 Year-to-year variations of the annual mean latent heat plus sensible heat fluxes averaged over the regions of the Gulf Stream ([85-50W, 25-45N], red) and Kuroshio ([120-150E, 20-40N], black).

the ocean? Second, water vapor is an important greenhouse gas. As the temperature of the Earth's surface and atmosphere increases, the atmosphere is able to hold more water vapor. The additional water vapor, acting as a greenhouse gas, absorbs energy that would otherwise escape to space thereby causing further warming. How much of the global warming can be attributed to the increased water vapor? Finally, the salinity in the ocean mixed layer would increase due to the loss of water vapor to the atmosphere, with consequent impact on the thermohaline circulation that is strongly influenced by the surface salinity differences between the subpolar and the subtropical oceans. The increase in surface salinity also affects the mixed layer structure over the global oceans, which further influences the way that the ocean and the atmosphere interact. To gain a better understanding of the role of evaporation in the ocean climate, salinity observations are needed.

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Global Oceanic Precipitation Variations

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The CAMS-OPI Global Monthly Precipitation Analysis

Prior to 1979, virtually the only information available on oceanic precipitation came from rain gauges at coastal and island stations, along with ship observations of sensible weather. While these data were sufficient to permit the estimation of long-term mean oceanic precipitation (Jaeger 1976; Dorman and Bourke 1979, 1981; Legates and Wilmott 1990), they were not adequate to enable the creation of time series of oceanic precipitation. Significant progress has been made in the last two decades in quantitatively documenting oceanic precipitation, thanks to the advent and continuous operation of earth-observing satellites. Many algorithms have been developed and applied to generate precipitation estimates from satellite-observed radiance emitted or reflected from clouds, precipitation and the earth's surface. Precipitation analyses based on these estimates have been developed to make possible scientific studies of rainfall variation over the globe. Two of the most used of such products are the CMAP (CPC Merged Analysis of Precipitation, Xie and Arkin, 1997) and the GPCP (Global Precipitation Climatology Project, Adler et al., 2004). CMAP and GPCP are both based on the combined use of several estimates of precipitation derived from satellite observations together with observations from rain gauges, and have been shown to be superior to other available data sets for monitoring and studying global precipitation (Adler et al., 2001).

Unfortunately, due to the requirement to collect gauge observations from around the world and to occasional delays in obtaining some of the necessary satellite products, neither CMAP nor GPCP are available until several months following the end of any given time period. Thus near real-time monitoring of global precipitation, such as is discussed here, relies on more promptly available products using similar methods to those used for CMAP and GPCP. One such satellite data set is the outgoing longwave radiation (OLR) observed by the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites beginning from June 1974 (Gruber and Krueger 1984). The OLR data measures the intensity of infrared radiation emitted from clouds and the earth's surface toward space. Precipitating clouds, which often exhibit high and therefore cold cloud tops, can be identified in the OLR data as regions of low OLR values because colder clouds emit less infrared radiation. In particular, the convective clouds that produce most of the oceanic precipitation over the global tropics and subtropics tend to produce more precipitation when they have higher tops and therefore less OLR (Janowiak and Arkin 1991). Quantifying this relationship, Xie and Arkin (1998) developed an algorithm to derive estimates of monthly precipitation from the NOAA OLR data based on a set of seasonally and regionally varying empirical relations between precipitation and OLR. The precipitation estimates, which are called the OLR-based Precipitation Index (OPI), have been produced for the 32-year period from 1974 to the present. Verification tests against independent gauge observations have shown that the OPI is able to depict spatial and temporal variations of precipitation over both land and ocean for most of the globe with quantitative accuracy comparable to most other satellite-based products (Adler et al. 2001).

To further improve the quality of precipitation analysis over land, Janowiak and Xie (1999) developed a method to combine the OPI estimates described above with a gauge-based analysis based on the station observations collected in the Climate Prediction Center (CPC) Anomaly Monitoring System (CAMS, Ropelewski et al. 1985). The CAMS is a climate data archive maintained by the NOAA Climate Prediction Center (CPC) that includes monthly surface air temperature and precipitation observation data from ~7000 meteorological stations over the global land areas and islands. The gauge-based analysis of monthly precipitation is constructed by interpolating the observations at the CAMS meteorological stations (Xie et al. 1996) through the algorithm of Shepard (1968) in which the weighting coefficients are inversely proportional to the distance between the station location and the interpolation grid point. This gauge-based analysis and the OPI satellite estimates are then combined over land, where the gauge data are used to determine the magnitude while the satellite data are used to define the distribution patterns of the precipitation fields. The final product of the CAMS-OPI monthly precipitation analysis is composed of this combined analysis over land and the OPI satellite-based precipitation estimates over ocean (Janowiak and Xie 1999). The CAMS-OPI is generated at NOAA/CPC on a real-time basis and is available for a 32-year period from 1974 to the present. Figure 1 presents an example of the spatial distribution of the OPI satellite estimates (top), the CAMS gauge-based analysis (2nd from top), number of the CAMS gauges in each 2.5°lat/lon grid box (2nd from bottom), and the CAMS-OPI product (bottom) for July 2005. Gauge stations collected in the

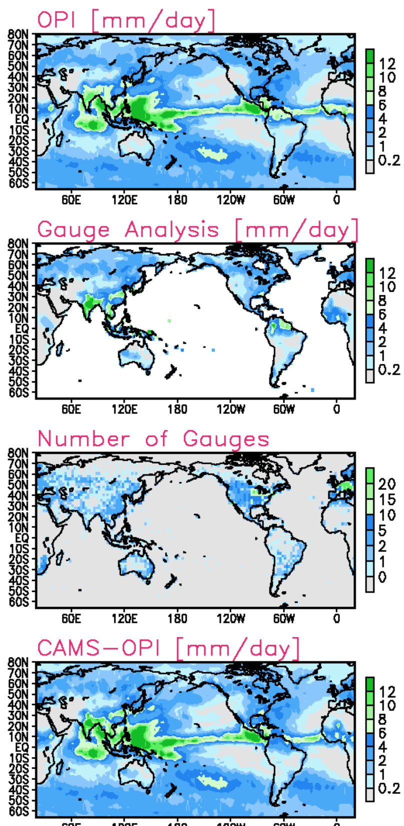

Fig.1: Spatial distribution of the OPI satellite precipitation estimates (top), the CAMS gauge-based analysis (2nd from top), number of the CAMS gauges in a 2.5°lat/lon grid box (2nd from bottom), and the gauge-satellite merged CAMS-OPI precipitation analysis (bottom), for July 2005.

CAMS data set are primarily located over populated land areas over North America, Europe, east coasts of Australia and China, while no gauges are available over desert areas over land and the vast of the oceanic areas.

The OPI satellite estimates are capable of capturing large-scale precipitation patterns over both land and ocean, while merging with the gauge data over land providing more details and improved accuracy of precipitation analysis over land.

Oceanic Precipitation Variations in 2005

Real-time monitoring of global oceanic precipitation is routinely conducted at NOAA's Climate Prediction Center (CPC) with the use of the gauge – satellite merged "CAMS-OPI" data set. As shown in Figure 2 (upper panel), global oceanic precipitation during 2005 is characterized by rain bands associated with the Inter-Tropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ), and the mid-latitude oceanic storm tracks.

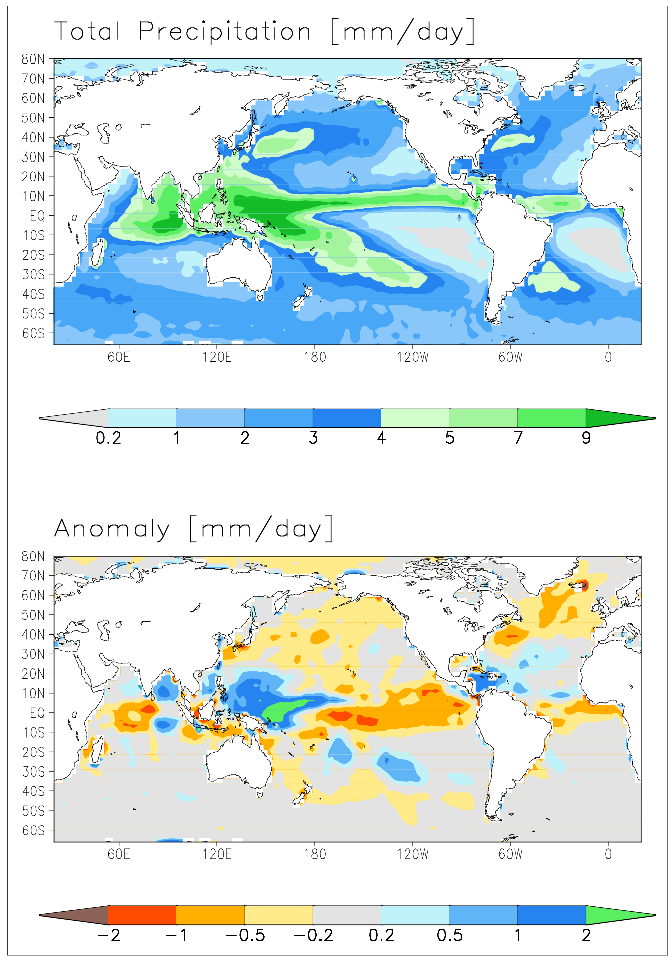

Fig.2: Annual mean total precipitation [mm/day, upper] and annual mean precipitation anomaly [mm/day, bottom] for 2005 as observed by the gauge-satellite merged data set of CAMS-OPI (Janowiak and Xie 1999). Precipitation anomaly is calculated using 1979 – 1995 as the base period.

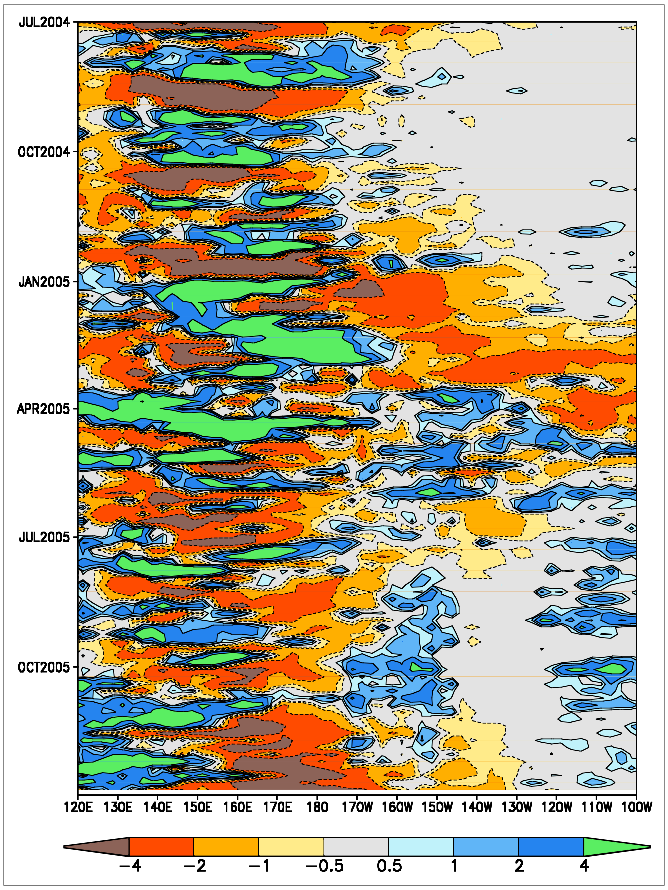

Fig. 3: Time-longitude section of precipitation anomaly averaged over the tropical Pacific [5°S-5°N] as observed by the Global Precipitation Climatology Project (GPCP) pentad precipitation data set (Xie et al. 2003). Precipitation anomaly is calculated using 1979 – 1995 as the base period.

Mean precipitation over the entire global oceans during 2005 was 2.840 mm/day, equivalent to a fresh water influx of 1036.6 Kg/m^2. Maximum annual precipitation rates of over 10 mm day^{-1} are observed during the year over the tropical western Pacific where the ITCZ merges with the SPCZ. Meanwhile, relatively light precipitation was recorded over several oceanic dry zones over the southeast Pacific, northeast Pacific off the coast of Southwest United States, southeast Atlantic, tropical North Atlantic near western Africa, and the eastern Indian Ocean.

The distribution of precipitation anomalies during 2005 indicates a dipole pattern of wet and dry anomalies over the western and eastern tropical Pacific, respectively (Figure 2, bottom). Although weak El Niño conditions prevailed over the tropical Pacific in the second half of 2004 and continued into early 2005 (Lyon and Barnston 2005), enhanced precipitation was limited mostly to the tropical Pacific west of the dateline. This pattern is different from that typical of a medium or strong El Niño event when large positive precipitation anomalies occur over the central and eastern Pacific (Ropelewski and Halpert 1989, Xie and Arkin 1997).

Enhanced convection, and attendant above normal precipitation, was first observed in late 2004 over the tropical western Pacific north of Indonesia (Figure 2). As the positive precipitation anomaly moved slightly toward the east, it intensified and reached its maximum intensity during January – March of 2005. Strong variations in precipitation over the region at intraseasonal time scales are clearly indicated in Figure 3. These intraseasonal variations are associated with the strong Madden Julian Oscillation (MJO; Madden and Julian 1971) activity that was observed during that period (Climate Prediction Center 2005). The positive precipitation anomaly over the tropical western Pacific gradually shifted westward during the second half of 2005 as the coupled ocean-atmosphere system evolved toward a weak La Niña.

The second half of 2005 witnessed the most active tropical storm season on record. A total of 27 tropical storms occurred of which 14 developed into hurricanes, and 7 of those were classified as major hurricanes. These totals eclipse the previous records for the number of tropical storms (21 in 1933), number of hurricanes (12 in 1969) and 1 short of the record year for the number of major hurricanes (1950). As a result, a substantial positive precipitation anomaly was observed over the regions of strong hurricane activity, especially over the Caribbean Sea. Note that the Atlantic ITCZ was located slightly north of its climatological latitude, which is reflected by two parallel bands of positive and negative precipitation anomalies over the tropical Atlantic (Figure 2, bottom).

Also noticeable during 2005 is the substantially depressed precipitation over the northwestern Atlantic. A brief examination of monthly precipitation and atmospheric circulation fields suggest that the bulk of the negative precipitation anomaly over the region was the result of below normal winter storm activity in the oceanic storm track, which is a climatological feature over the western North Atlantic during the cool season. This reduced storminess was associated with the strong anticyclonic blocking activity over the high latitudes that was observed during the winter season.

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Atlantic Monthly Air-Sea Fluxes and the 2005 Hurricane Season

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Air-sea fluxes in the 10˚-20˚N belt across the Atlantic exhibited anomalies that are consistent with the increased tropical activity during 2005. An assessment of Atlantic fluxes is conducted with a newly completed version of the Florida State University air-sea flux fields (the FSU3). The FSU3 are produced using an objective analysis technique (Bourassa et al. 2005) that produces fields of surface turbulent fluxes and related variables. Much of the energy that goes into increasing the intensity of a tropical disturbance or tropical cyclone (TC: tropical depressions, tropical storms, and hurricanes) comes from latent heat release related to condensation (i.e., water vapor changing phase to liquid water. This water vapor (and the energy associated with it) originates as liquid water in the ocean. The latent heat flux (LHF) is the rate (per unit area) at which energy associated with the phase change of water is transferred from the ocean to the atmosphere. In the Atlantic hurricane generation region, the area averaged 2005 LHF anomaly is 10 Wm^{-2}, 20% greater than the largest similarly averaged anomalies seen in the 1978 to 2003 time series.

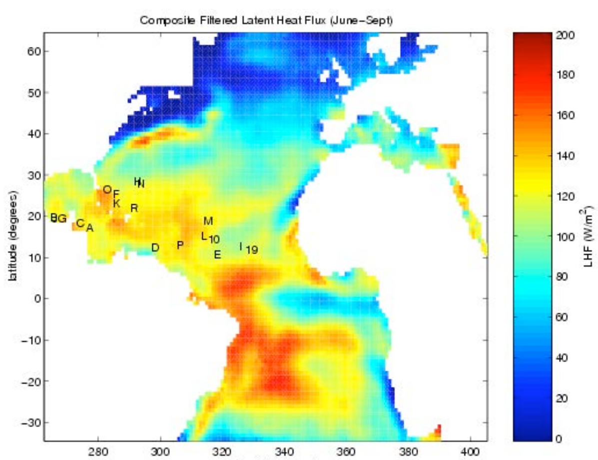

Figure 1. Composite latent heat flux from June to September 2005. The letters are the first letters of the named storms, located where they were first identified as TCs by the National Hurricane Center. The numbers indicate similar positions for tropical depressions that did not become named storms. TC formation favored areas of high LHF, but were found outside areas of maximum LHF.

Latent heat fluxes are largely dependent on the wind speed and the difference in humidity between the surface and an arbitrary height above the surface (typically 10 meters). In 2005 the mean wind speeds were near average. However, there was a small drop in the 10m humidity with a large increase in the near surface humidity (due to an increase in the SSTs). The drop in 10m humidity associated with a prolonged increase in moisture flux suggests that the moisture is being spread over a larger boundary layer and/or removed from the boundary layer with unusual efficiency. It is likely that TCs were responsible for removing an unusually large amount of moisture from the boundary layer. In addition, SSTs in 2005 were atypically greater than the air temperature, resulting in relative instability in the boundary layer. This relative instability implies a thicker boundary layer and more easily generated convection, which would lead to more tropical disturbances growing into TCs. A thicker boundary layer could result in more moisture in the boundary layer despite a reduction in 10m humidity.

The LHF varied considerably across the Atlantic Ocean with peak anomalies near 55 Wm^{-2} on the southern side of the ITCZ in July and August. In September, the highest positive LHF anomalies shifted northwestward to the region from east of Florida to Bermuda. September tropical cyclone formation mimicked this NW shift. A June-September composite (Fig. 1), with the location where TCs were first identified, shows that preferred genesis regions were areas of high LHF. The hurricane genesis region had unstable stratification in the boundary layer; meaning that information about the low level winds was relatively well translated to the surface (10m) winds. The 10 m wind anomalies indicated a weakening of the normal low-level easterlies, which would tend to reduce low level vertical wind shear. Low shear is a positive factor for development of tropical systems. We suspect that the combination of abundant energy (in the form of water vapor) combined with increased boundary layer instability and reduced vertical shear led to exceptionally favorable conditions for the genesis of tropical cyclones in 2005.

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Surface Currents

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Ocean surface currents (Fig. 1) carry water, heat, salt, nutrients and other properties over vast distances and play a major role in regional and global climate. The Ocean Observing System for Climate measures surface currents in-situ by an array of satellite-tracked drifting buoys and by moored current meters at a number of sites. NOAA/AOML processes and distributes the drifter data as part of the Global Drifter Program, while data from the fixed-location moorings are processed and distributed by NOAA/PMEL as part of the Tropical Atmosphere Ocean Project.

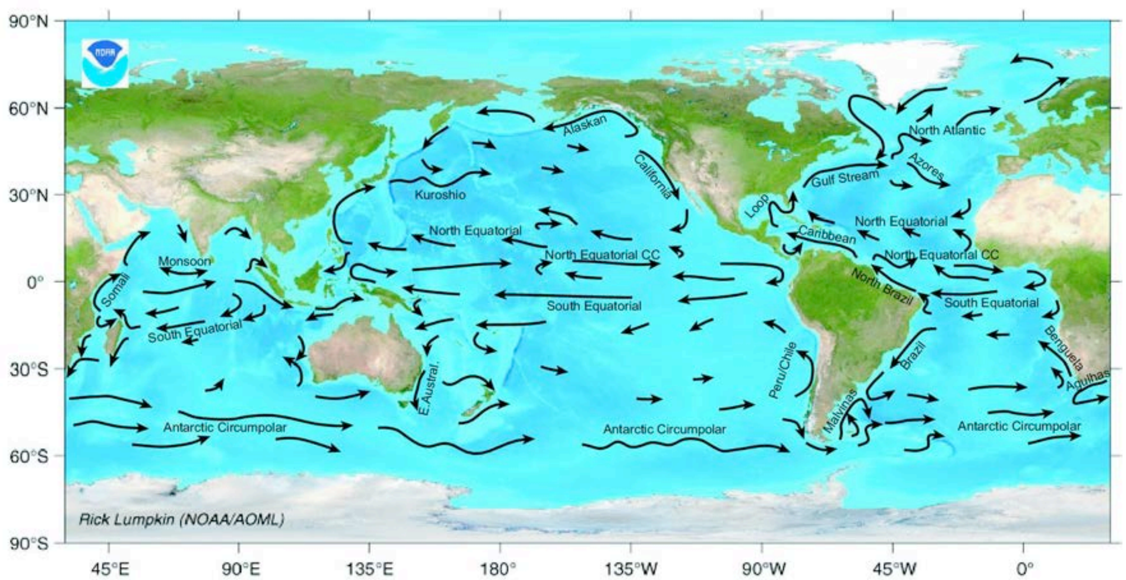

Fig. 1: Major ocean surface currents of the world, derived from drifter data. "CC" stands for counter-current.

Why surface currents are important for climate

Ocean surface currents are a critical part of the earth's heat engine. Incoming solar heat in the tropics must be carried poleward by the ocean and atmosphere to achieve a steady-state balance; ocean transport by currents dominates the net transport for tropical latitudes (Trenberth and Caron, 2001). This tropical heat is lost to the atmosphere at higher latitudes (poleward of about 20º), creating the largest air-sea heat fluxes on earth and associated with the formation of denser water masses and the Meridional Overturning Circulation (MOC).

Time-mean heat advection can be calculated from averaged drifter trajectories and sea surface temperature (SST) measured by the drifters. The convergence or divergence of this transport (Fig. 2) shows where heat must be exchanged between the ocean and atmosphere in the form of air-sea heat fluxes. Heat convergence in Fig. 2 exceeds 200 W/m^2 in the Gulf Stream and Kuroshio Current, indicating enormous heat loss to the atmosphere in these regions. For reference, the largest sea-air heat flux in time-mean NCEP climatology is 255 W/m^2, found in the Gulf Stream extension. Large areas of heat divergence (blue in Fig. 2) are found in the Southern Ocean, particularly in the Indian Ocean sector, indicating where the ocean must absorb large amounts of heat from the atmosphere. (Interestingly, climatologies of air-sea fluxes, based on extremely sparse observations, are ambiguous about this feature; *c.f.*, Grist and Josey, 2003).

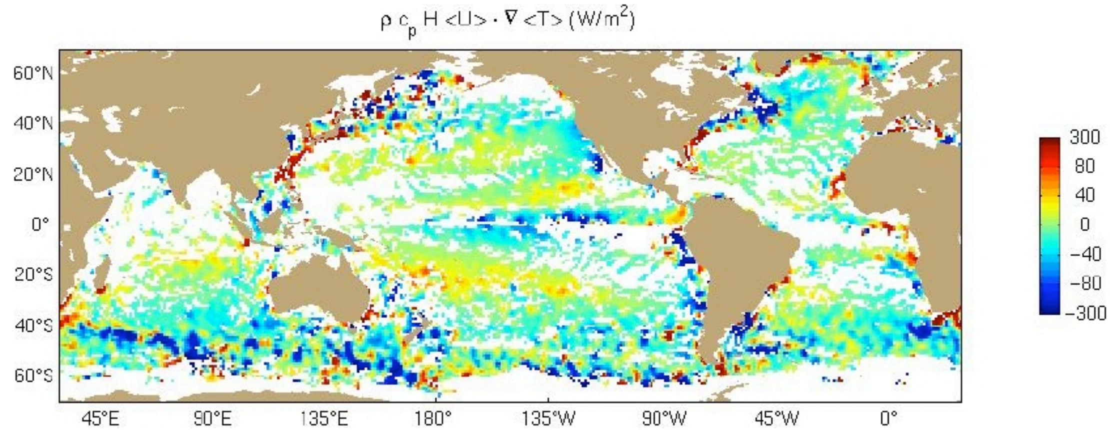

Fig. 2: Heat convergence (negative: divergence) driven by time-mean currents in the upper 30m of the ocean, in Watts per square meter. Red areas show where currents heat the atmosphere; blue areas are where the ocean cools the atmosphere. White areas are not resolved by the data.

Changes in the paths or strengths of surface currents can play a major role in climate fluctuations by altering the air-sea heat fluxes. For example, it is well known that SST differences between the northern and southern tropical Atlantic play a major role in setting rainfall rates in the Americas and Africa (Nobre and Shukla, 1996; Giannini et al., 2000), and that there should be a dynamical link between SST in these two regions via a positive feedback mechanism (Chang *et al.*, 1997). However, this link is not supported by observations (Enfield and Mayer, 1997), suggesting that heat advection by eddying currents acts as a major negative feedback (Seager *et al.*, 2001) that must be accounted for in order to improve seasonal rainfall forecasts.

What we can and cannot resolve with the existing observing array

The present in-situ observing system is capable of resolving time-mean currents and time-averaged eddy variability at 1° resolution throughout most of the world's oceans (Fig. 3). Coverage remains too sparse in a few regions, including the Gulf of Guinea in the eastern tropical Atlantic and in the northwestern Indian Ocean.

While the observing system is capable of a broad range of time-mean calculations, it is a greater challenge to produce continuous time series of current variations about this mean. Drifter observations can be averaged in extended zonal bins to map monthly anomalies (see below), while the moored observations provide continuous time series at points.

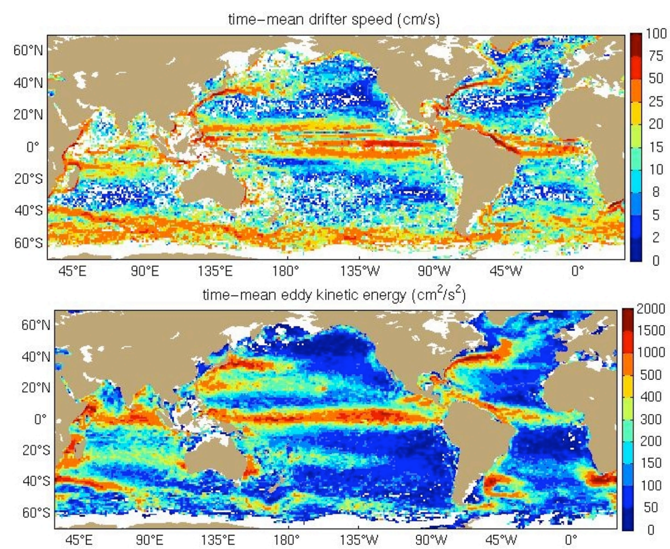

Fig. 3: Time-mean speed of drifters at 1° resolution (top). No interpolation has been used. White areas are not resolved by the data due to insufficient observations and/or extremely weak mean speeds. Bottom: eddy variability about the time-mean state (intensity of current fluctuations).

Current variations are associated with several types of motion. Large and mesoscale variations caused by sea level height can be inferred from satellite altimetry. These observations can be combined with in-situ observations of temperature, salinity and/or drifter trajectories (Fig. 4) for improved mapping of currents to investigate their spatial and temporal variability (Goni *et al*., 1996; Niiler et al., 2003). The availability of near-real time drifter and altimetry data also allow researchers to estimate and validate global current

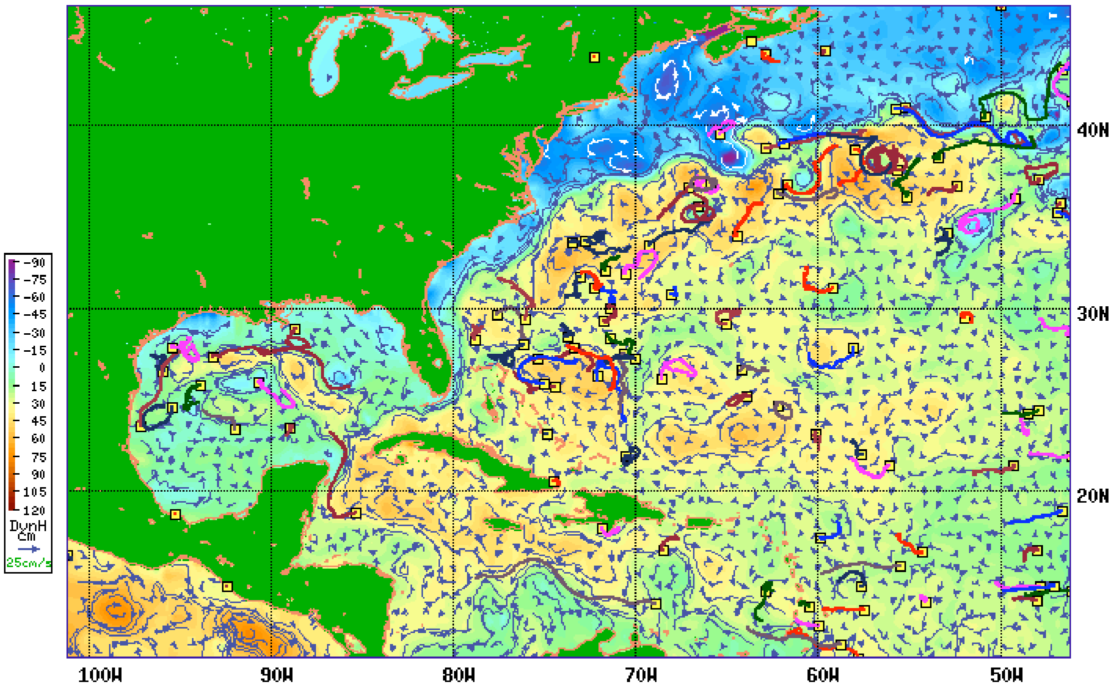

Fig. 4. Surface geostrophic current field in the North Atlantic derived from satellite altimetry during the period February 9-18, 2005, with drifter trajectories (color lines) corresponding during the period February 4-18, 2005. The dynamic height (color scale) derived from satellite altimetry is included in the map.

fields. Smaller scale, shallower changes are forced directly by wind stress anomalies, and can be estimated globally from satellite-based wind products using empirical models calibrated from the in-situ observations (Ralph and Niiler, 1999).

Ocean current measurements in 2005

For many years, the Global Drifter Program aimed at achieving an array of 1250 drifters, the number required to cover the world's oceans at a nominal resolution of 5ºx5º. In September 2005 the drifter array reached this target goal, becoming the first fully realized component of the Global Ocean Observing System. Growth of the array and its spatial coverage is shown in Fig. 5. By early 2006, the size of the drifter array had slightly exceeded 1250 due to near-concurrent dense deployments on some research cruises. With sustained funding, the drifter array will be maintained at 1250 with an instantaneous size fluctuating about this number. Future efforts must focus on improving the coverage of the array: some regions are very densely sampled, while other regions (typically upstream of the major shipping routes of Voluntary Observation Ships) are poorly sampled.

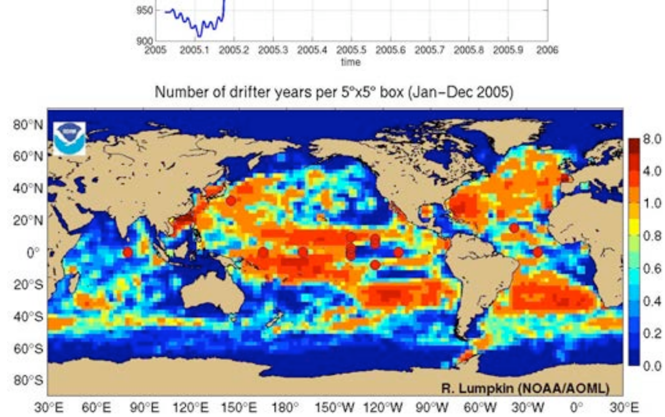

Fig. 5: Top: number of drifters in the Global Drifter Array. Bottom: drifter years of data at 5ºx5º resolution (shading) and location of moored near-surface current observations (red bullets) for January—December 2005.

Moored observations were collected at 14 sites (red bullets in Fig. 5), including equatorial regions of surface divergence where drifting buoys do not reside for long. Studies of the continuous currents at these sites have greatly improved our understanding of how current variations drive off-equatorial heat fluxes (e.g., Grodksy et al., 2005).

During 2005, surface currents were well sampled except in the far northern Pacific, the southwest Pacific between 20—40ºS, 150ºE to the dateline, the Arabian Basin of the Indian Ocean and the extreme Southern Ocean south of 55ºS.

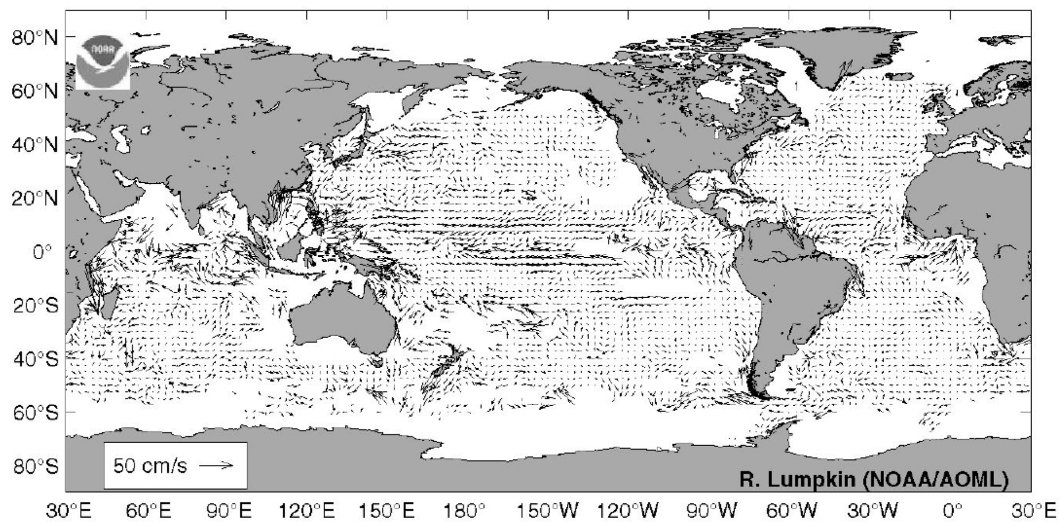

Fig. 6: 2005 mean anomalies from ten year surface current climatology.

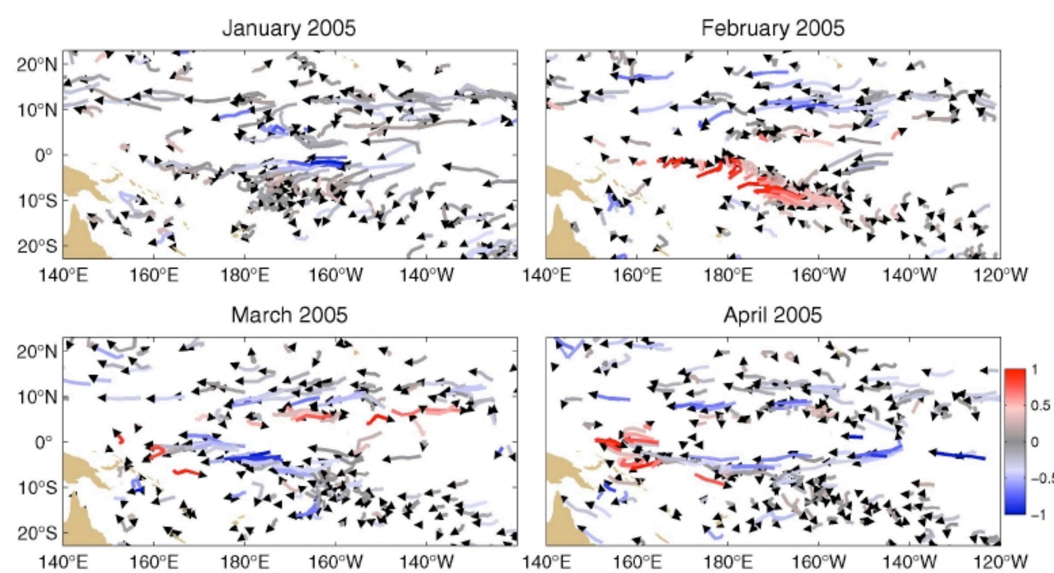

Fig. 7: drifter trajectories during January—April 2005 in the tropical Pacific. Arrowheads indicate direction; color indicates zonal speed anomaly (m/s, positive eastward).

State of Ocean: Currents in 2005

A climatology of monthly mean currents was computed from all drifter observations, 1994—2004, using the methodology of Lumpkin and Garraffo (2005). Anomalous currents (Fig. 6) were calculated with respect to this climatology.

Indo-Pacific Basins: Annual mean anomalies from climatology (Fig. 6) were most prominent in the tropical Pacific Ocean. Westward anomalies of nearly 20 cm/s were observed on the equator between 120ºW and the dateline. Weaker anomalies of 5-10 cm/s were seen in the North Equatorial Current (NEC) region (10-20ºN) (see Fig. 1). The drifter observations did not indicate anomalously strong eastward currents in the Kuroshio Extension, at odds with the simple hypothesis of a more intense than average wind-driven clockwise gyre.

The strongest intraseasonal (timescales between mesoscale eddies and the seasonal cycle) anomalies were observed in early 2005 in the western and central tropical Pacific, associated with equatorial wave activity driven by intraseasonal ("Madden-Julian Oscillation") wind fluctuations (c.f., Eisenman *et al*., 2005). In January (Fig. 7), very strong westward anomalies were measured in the northern branch of the South Equatorial Current (nSEC). The nSEC at 160ºW-170ºE, 0-5ºS was 80-100 cm/s westward, compared to a climatological January speed of 40-60 cm/s. During February, a dramatic reversal was seen from 155ºW—180º, 6—12ºS where several drifters moved eastward at 50-100 cm/s. Drifters suggested the passage of a second equatorial wave in March and April, when strong westward, then eastward, anomalies were seen west of the dateline (Fig. 7). These anomalies were also present in the continuous time series of near surface currents measured at the Tropical Atmosphere Ocean (TAO) mooring at 0, 170ºW (Fig. 8). The previously noted NEC anomalies were first observed in February. Westward anomalies in the South Equatorial Current (SEC) at 0—6ºS appeared in April. Both the NEC and SEC continued to flow anomalously quickly through the remainder of the year.

For the major western boundary current of the Indian Basin, the Agulhas Current, altimetric estimates of geostrophic transports suggest that the 2005 annual mean remained slightly lower than its historical value, and significantly lower (5-10 Sv) than during 2004 (Fig. 9).

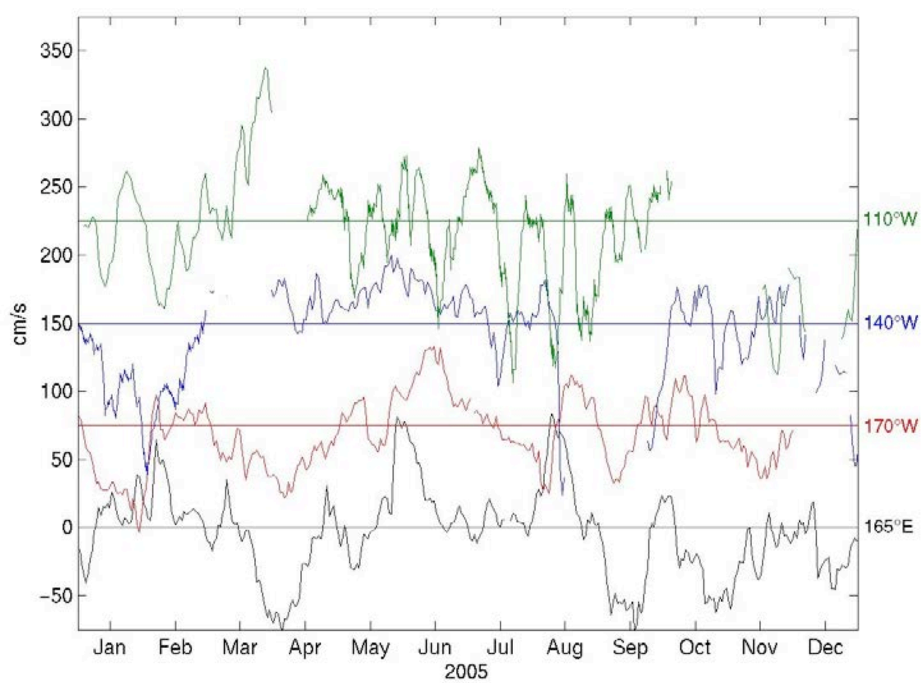

Fig. 8: near-surface zonal current anomalies (daily averages) measured at equatorial TAO moorings. Time series east of the dateline have been displaced vertically; the zero line for each is color-coded.

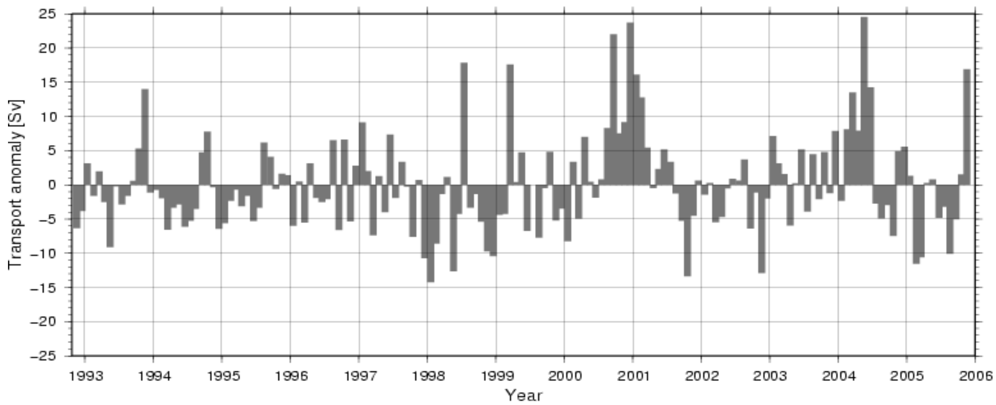

Fig. 9. Monthly geostrophic transport anomalies of the Agulhas Current at 28°W, derived from satellite altimetry observations.

Atlantic Basin: Several key components of the Atlantic Meridional Overturning Circulation can be monitored using altimetry observations. For example, the shedding of Agulhas Current rings is closely related to pulses in the current and represents the main passage of surface waters from the Indian into the Atlantic Ocean. The number of Agulhas Current rings has a very large year-to-year variability and can be monitored from space-time diagrams of sea height anomalies (Fig. 10, left). Similarly space-time diagrams off the coast of NE Brazil can be used to identify and track the rings of the North Brazil Current. These rings contribute with the transfer of South Atlantic surface waters into the North Atlantic (Fig. 10, right). During 2005 the number of rings shed by the Agulhas and North Brazil currents remained close to their mean annual value.

The North Atlantic subtropical gyre –benchmarked by transport through the choke points of the Florida Straits and Yucatan Channel – was close to its decadal climatological strength during 2005. The Western Boundary Current transport through the Florida Straits, measured by cable voltage, averaged 31.4±1.2 Sv during 2005 (C. Meinen, pers. comm.), not significantly different from the 1982—2005 mean of 32.1 Sv. Transport through the Yucatan Channel (from the Caribbean Sea to the Gulf of Mexico), estimated from altimetric sea level anomaly was within 1 Sv of the long-term mean. In the North Equatorial Current region 5—15ºN, 30—50ºW, westward anomalies of 10 cm/s were observed. Drifter deployments during several French cruises seeded the Gulf of Guinea region heavily for the first time; anomalies here were large, but may reflect a poorly-defined climatology for the period 1994—2004. Thus, it is difficult to tell from these data what role anomalous advection may have played in the development of the unusually large cold tongue during 2005.

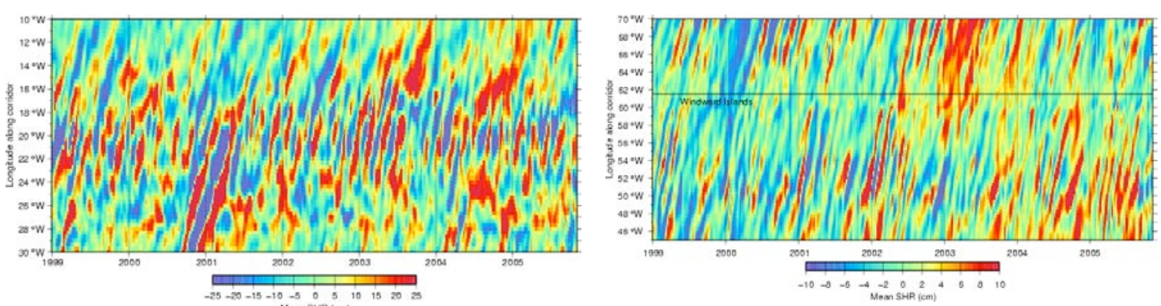

Fig. 10. Space-time diagrams of sea height anomalies depicting the motion of the Agulhas Current (left) and North Brazil Current (right) and the rings shed by these currents during the period 1999-2005. The reds and yellows (blues) indicate large (small) values of sea height anomalies.

Southern Ocean: Drifters did not reveal large-scale anomalies in the strength of the Antarctic Circumpolar Current (Fig. 5). During the period August to December, 18 drifters passed south of Cape Horn. These drifters indicated that the flow entering the Drake Passage was 8±9 cm/s, much weaker than the climatological speed of 23±11 cm/s here. This anomaly was most prominent during August—September. Four drifters passed through this region during February—May, measuring speeds of 27 ±14 cm/s (very close to climatology).

ACKNOWLEDGEMENTS

Drifter data is distributed by NOAA/AOML's Global Drifter Program at the Drifter Data Assembly Center web site (http://www.aoml.noaa.gov/phod/dac/dacdata.html). Moored current meter data is distriubed by NOAA/ PMEL's Tropical Atmosphere Ocean project at http://www.pmel.noaa.gov/tao. Altimetric time series of transports may be viewed at http://www.aoml.noaa.gov/phod/altimetry. The authors were supported by NOAA's Climate Program Office and the Atlantic Oceanographic and Meteorological Laboratory.

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The Meridional Overturning Circulation and Oceanic Heat Transport

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Introduction

Oceanic and atmospheric circulation drives climate variability through the redistribution of heat about the globe. The contribution of the ocean dominates the system equatorward of 17ºN and 17ºS and plays a sizable role at the higher latitudes according to recent atmospheric reanalyses (Trenberth and Caron, 2001). A prominent example of the physical processes of coupled ocean-atmospheric meridional heat transport is the well-known El Niño-Southern Oscillation phenomenon. On longer time scales, the component of the ocean circulation associated most with variability in heat redistribution is the Meridional Overturning Circulation (MOC), sometimes also called the thermohaline circulation. The MOC is a global circulation cell wherein surface waters in the high latitudes are cooled in winter, thereby becoming denser, and this dense water sinks and flows towards the equatorial regions. In tropical and subtropical regions around the world these waters eventually mix with other waters, becoming less dense, and they return to the sea surface to flow towards the higher latitudes and complete the cell, simultaneously carrying a significant amount of heat to the higher latitudes. The primary locations where deep convection occurs are in the northern North Atlantic and in the subpolar ocean around Antarctica, while the upwelling of new surface waters is spread broadly around the globe.

There are other convective circulation regimes in the global ocean (e.g. Subtropical Overturning Cells), however the term MOC is generally reserved for only the deepest overturning cells. The shallower overturning cells are not insignificant for climate; for instance while the redistribution of anthropogenic carbon in the ocean is dominated by the MOC in the northern North Atlantic, the shallower cells which form the Subantarctic mode waters in the southern hemisphere sequester a substantial amount of carbon (Sabine *et al.*, 2004). These other shallow overturning circulations are intricately tied to gyre scale circulations and as such the variability of these circulations are difficult to quantify using the present ocean observing system and present an active research topic.

This chapter focuses on the current state of knowledge about the MOC and its associated heat transports in part because of the more advanced state of the ocean observing and analysis system in place to describe MOC variability. In the North Atlantic, the MOC can be studied at discrete locations, or choke points, while in the Southern Ocean deep convection is not geographically isolated and is closely tied to the Antarctic Circumpolar Current. Any observing system in the Southern Oceans is a practical challenge for these reasons as well as due to the simple logistical problems of working in the Southern Ocean climate. Present research suggests that the deep convection in the MOC in the North Atlantic (formation of the so called North Atlantic Deep Water, NADW) represents about half of the total deep-water ventilation, the Southern Ocean representing the other half (Orsi *et al* 2001). This chapter will focus on the component of the MOC associated with deep-water formation in the northern North Atlantic where the observing system is more advanced.

Variations in the strength of the overturning circulations are directly related to variations in heat transport (warm water flowing north in the upper layers and returning southward as cold water at depth represents a net poleward heat transport). The current best estimates for the steady state global mass and heat transport can be found in the analyses of Ganachaud and Wunsch (2003) as shown in Figure 1 (see also Talley, 2003). Keep in mind that oceanic heat transport is not just carried by the Atlantic MOC. Many shallow overturning circulations exist that are also important for carrying heat. For example the North Pacific carries about 0.5 PW northward, but most of this heat transport is associated with water mass transformations in the upper layers of the ocean where warm surface water is cooled (transformed) into shallow North Pacific Intermediate Water. On the other hand, the North Atlantic carries a much larger transport of 1.2 PW northward, most of which is carried in the top-to-bottom MOC system where warm surface water is transformed into deep and bottom water. Historical estimates of the net northward Atlantic MOC heat flux in the vicinity of its maximum,

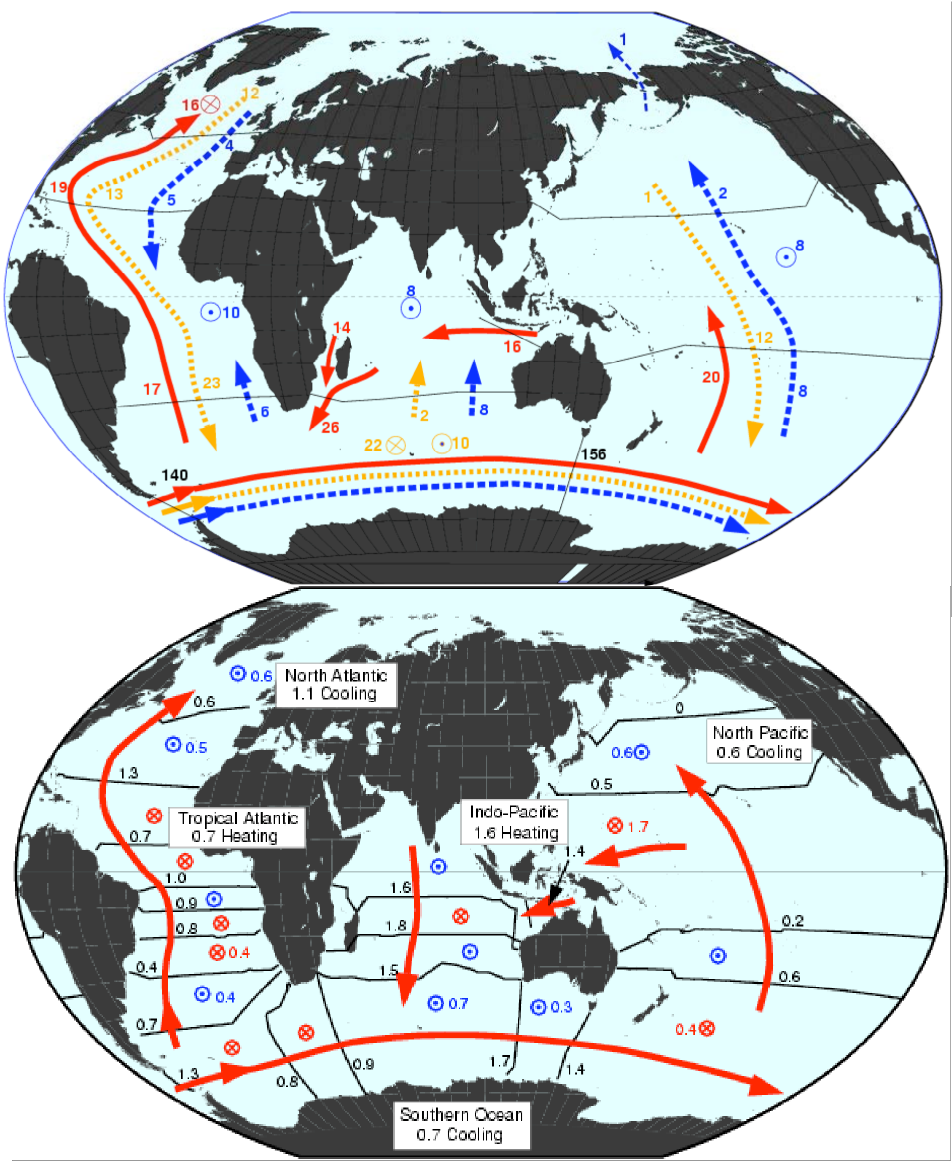

Figure 1: Estimates of the meridional transports of top) mass and bottom) heat from the globally consistent results from Ganachaud and Wunsch (2003 adapted from Macdonald et al 2001), using WOCE era hydrographic sections (black lines). top) Red arrows indicate the direction of mass transport in surface waters, Yellow represents intermediate water masses (e.g. NADW) and Blue represents Bottom waters. Units are in 10^9 kg s^{-1}. Circles with dots are upwelled water, circles with X are downwelled/convected water. bottom) Red arrows represent direction of heat transport (totals given across each section). Blue (red) circles with dots (Xs) are heat loss (gain) to the atmosphere.

which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[2] to 1.6 PW, while estimates of the oceanic heat transport in the 30°S to 35°S band in the South Atlantic are even more uncertain, ranging from small southward values to more than 1 PW northward.

Direct estimates of the MOC

NOAA maintains some of the longest time series of observations aimed at monitoring the MOC in the North Atlantic. Begun in 1982 as the Subtropical Atlantic Circulation Study (STACS), the NOAA program has been monitoring variations in the upper limb of the MOC by measuring the Florida Current transport almost continuously using a submarine cable across the Florida Straits[3], while the deep limb of the MOC has been monitored through regular hydrographic cruises (more than 20 to date) across the Deep Western Boundary Current east of the Bahamas. Called the Western Boundary Time Series (WBTS) project in its current incarnation, the NOAA program now involves moored inverted echo sounders and bottom pressure gauges east of Abaco Island in the Bahamas as an effort at time series monitoring of the Deep Western Boundary Current in addition to the regular hydrographic cruises. NOAA is also collaborating in an international program to measure the total basin-wide heat transport at 26ºN in the Atlantic

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[2] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports. One PW is equivalent to the amount of energy produced by about one million nuclear power plants.

[3] Over 24 years of daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-service cables spanning the Straits of Florida. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory.

using a variety of measuring systems. Called the Meridional Overturning Circulation Heat-Transport Array (MOCHA) by the US contributors (NOAA/AOML and the Univ. of Miami with NSF funding) and the RAPID climate change program by the UK contributors (National Oceanography Centre, Southampton), the program began in 2004 with the stated goal of developing a cost-effective basin-wide MOC monitoring system.

The Florida Current contains most of the upper limb of the MOC as it flows through the Florida Straits, with a smaller contribution being carried by the Antilles Current east of the Bahamas. Fluctuations in the Florida Current show a clear negative correlation with the atmospheric phenomenon known as the North Atlantic Oscillation (NAO); however while the NAO has been trending towards its negative extreme over the past twenty years, the Florida Current transport shows no such long-term trend through 2005 (Figure 2). The

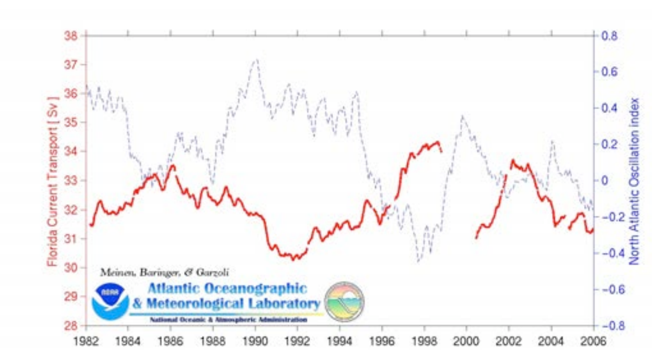

Figure 2: Florida Current transport (red solid) as measured by the NOAA funded submarine cable across the Florida Straits, along with the North Atlantic Oscillation index produced by NCEP (blue dashed).

annual mean transport observed in 2005 (31.4 Sv[4]) falls just within the lowest quartile of historical annual mean transports from the cable, however this transport is still well within one standard deviation from the long-term mean of 32.1 Sv and given the statistical standard error of the mean of 1 Sv, the year 2005 cannot be termed as an unusual year in terms of the Florida Current transport (Figure 3).

Hydrographic observations of the lower limb of the MOC, mostly contained within the Deep Western Boundary Current east of the Bahamas, show the arrival of a pulse of new NADW in 1995, with a gradual

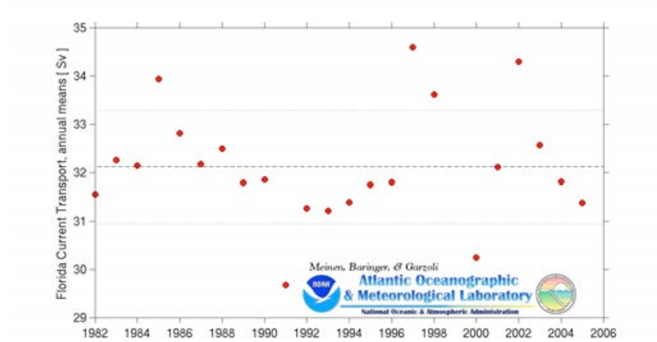

Figure 3: Annual mean transports from the Florida Current measured by submarine cable.

extension of this signal offshore occurring later albeit of smaller magnitude (Figure 4). In 2005 the hydrographic observations showed little change from the previous several years. Coupled with the new NOAA-funded system for monitoring the Deep Western Boundary Current and the new international program for monitoring the basin-wide circulation, in future years it will be possible to state with a much greater degree of certainty what the variations in the integrated,

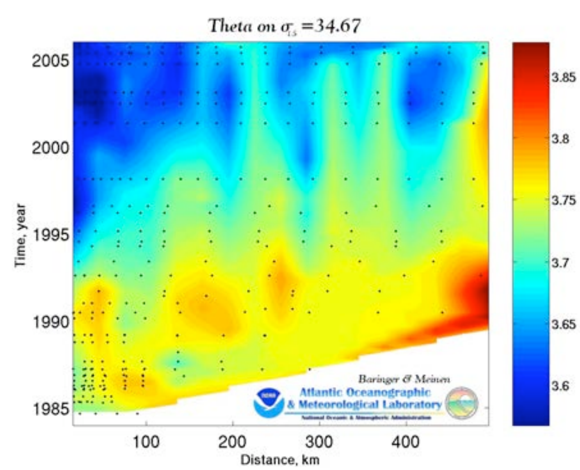

Figure 4: Potential temperature (theta) obtained east of Abaco Island as part of the NOAA Western Boundary Time Series project. Theta is shown on a potential density surface associated with the upper core of the Deep Western Boundary Current. During the 1980's sections only extended 100-300 km offshore that were extended farther offshore in the 1990's to the present.

basin-wide, MOC circulations are and at what time scales they vary. In a recent article, Bryden *et al.*

[4] Sv is a Sverdrup or 10^6 m^3/s, a unit commonly used for ocean volume transports.

(2005), postulated a 30% reduction in the MOC transport between the 1950s and the present day, however that analysis was based on a very limited data set (essentially five points), and other data over the past few decades, such as the moored observations of the Deep Western Boundary Current at the Southeast Newfoundland Rise in the early 1990s and early 2000s showed no indication of such a significant trend in the MOC (Fritz Schott, personal communication).

Heat transport estimates

A basin-wide MOC monitoring system such as the one now in place is truly needed to measure the real ocean variability; however more limited programs currently in place can address individual aspects of the MOC, such as estimating the heat transport using the long time series of expendable bathythermograph (XBT) observations collected on two trans-Atlantic sections by NOAA/AOML. AOML collects XBT data on two lines spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along a line running between Spain and Miami, Florida (denoted AX7) and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along a line between Cape Town, South Africa and Buenos Aires, Argentina (denoted AX18). These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data can also be usefully augmented with other data from the NOAA funded WBTS program measuring the Florida Current.

Heat transports have already been successfully computed using XBT data (see Roemmich *et al*, 2001, Garzoli and Baringer 2006). Because flux estimates depend upon density, and hence upon salinity, these results have depended on how well salinity profiles could be estimated to complement the XBT data and on how the flux is estimated for depths not sampled by XBT observations. Improving these estimates to achieve more accurate fluxes has been an essential part of this a project at AOML throughout 2005, as has been a careful quantitative assessment of the accuracy of the resulting fluxes.

Estimates of mass and heat transport have been obtained from temperature profiles collected along AX07 and AX18 high-density lines using Sippican T-7 XBT probes, which typically provide data to 800 m or deeper. Salinity was estimated for each profile by linearly interpolating the closest of Levitus' climatological mean salinity and temperature profiles to the XBT temperature and the climatological profiles were used to extend the data to the bottom. In computing velocities the flow is assumed to reverse direction just below the northward flowing Antarctic Intermediate Water (σ_0=27.6 kg m^{-3} in the North Atlantic and σ_0=27.4 kg m^{-3} in the South Atlantic) based on historical studies in the literature and based on what is known about the circulation (hence water deeper than this flows southward). Within strong flows such as the Florida Current or the Malvinas Current the water moves in the same direction down to the bottom and the transport must be specified (e.g. by the utilizing the mean value of the Florida Current from the WBTS submarine cable observations for AX07). The estimated velocities have been adjusted so that the net mass transport across the basin is zero using a single velocity correction for each section. Typically, values of this correction are extremely small, ranging from 10^{-4} to 10^{-6} m s^{-1}.

Using data from 1995 to the present in the North Atlantic, the averaged heat transport was found to vary on inter-annual time scales from 0.8 ± 0.2 PW to 1.2 ± 0.2 PW (Figure 5). The annual average for 2005 was 0.96 PW, indistinguishable from the 1995-2005 average heat transport. Heat transport due to wind-driven Ekman layer flow computed from annual Hellerman winds was relatively small (only 0.1 PW). The observed variability is entirely a function of changes in the

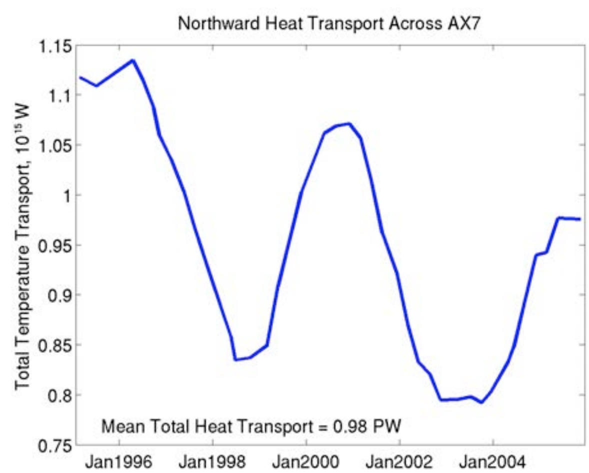

Figure 5: North Atlantic Meridional Heat transport along the AX7 high density XBT line (blue solid line). One PW is equivalent to the amount of energy produced by about one million nuclear power plants. Quarterly values of heat transport vary from 0.5 to 1.6 PW (not shown) for each of the sections (1 PW = 10^{15}W) and here the heat transport and NAO index are subject to a Gaussian filter with e-folding time scale at 1 year.

interior density field; the barotropic Florida Current transport was kept fixed (32 Sv), despite variations in the Florida Current. As shown earlier the 2005 annual mean Florida Current transport of 31.4 Sv was only slightly lower than the 1982-2005 mean value of 32.1 Sv. Planned future improvements to the North Atlantic upper ocean heat transport estimates include (i) taking into account time varying Florida Current transports and wind fields, (ii) improving salinity estimates and extrapolations to the bottom, and (iii) improving error estimates that reflect the effect of the initial reference level, the wind field variability, the importance of barotropic flows, and the uncertainties of the salinity estimates and the extrapolations.

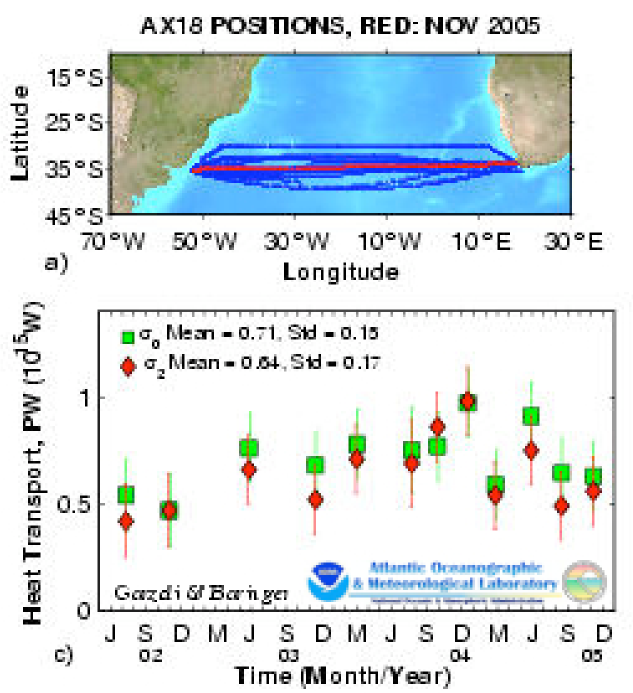

Figure 6: South Atlantic Meridional Heat transport along the AX18 high density XBT line. Heat transports were estimated using two different techniques: one where the flow is assumed to reverse direction just above Antarctic Intermediate Water (green squares) and one where the flow is assumed to reverse direction just above Antarctic Bottom Water (red diamonds).

For the South Atlantic, the transports must be adjusted for the strong flow of the Malvinas Current that is unidirectional (barotropic). Note that in the North Atlantic a good estimate for the barotropic western boundary current is readily available through Florida Current observations and a stable estimate of the mean transport. In the future, current meter moorings deployed by French scientists in the Malvinas Current will provide these values for the South Atlantic, however at this date there is no long-term time series of the Malvinas Current. Based on the limited data available for 2002-2005, the mean heat transport is northward with a mean of about 0.64 +/- 0.3 PW (Figure 6). The 2005 mean heat transport is about 0.59 PW and is indistinguishable from the 2002-2005 mean. Similar improvements to the North Atlantic transports are planned for the South Atlantic. Data collected along the A10 WOCE line located near 30°S have been used to estimate the errors induced by using a climatological deep T, S field from the Levitus product instead of actual data. Results indicated that this procedure can introduce an error of up to 25% and that in order to reduce the errors a better climatology and better T/S relation is needed.

Additional results indicate that the use of different wind products to calculate the wind-driven Ekman component of the flow induced an error of 10%. Particularly in the South Atlantic, the wind-driven Ekman transport estimates vary with latitude and season. One of the main challenges to providing an accurate heat transport is the lack of accurate information on the South Atlantic boundary currents. As a result providing estimates in the South Atlantic is in many ways more challenging than in the North Atlantic.

Summary

Preliminary estimates of the temperature transport in the North Atlantic from the available long-term data sources suggest that the annual mean heat transport estimates range from values near 1.2 PW to values near 0.8 PW with large interannual fluctuations. Changes of the heat transport on the order of 30% such as that postulated by Bryden *et al.* (2005) could have substantial impacts on climate, and time series observations are clearly necessary in order to put one-time hydrographic sections in temporal context. Temporal aliasing is a well-known problem in the use of snapshot sections, and some kind of moored observing system will be needed into the future to monitor fluctuations of the MOC system. Repeated hydrographic sections, however, can play a significant role in measuring and monitoring the MOC system over a broader range of locations than would be feasible with moored instrumentation, particularly when the hydrographic section data is obtained with a fairly high frequency as with the quarterly XBT sections discussed earlier. The programs in place in 2005 are an excellent first step towards the development of such an integrated measurement system, however much work remains before it will be possible to state that the Atlantic MOC system is truly being monitored.

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Ocean Heat Content Variability

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Introduction

Assessment of the role of the ocean in global climate variability requires accurate time-dependent estimates of ocean heat and fresh water content as well as transports of both quantities over the globe. Phenomena such as El Niño, the Pacific Decadal Oscillation (Mantua et al. 1997), the North Atlantic Oscillation (Hurrell 1995), and the global water cycle are all aspects of climate in which ocean heat and freshwater content and transport variations play a role. Analyses of how temperature and salinity anomalies enter, circulate within, and leave the ocean lead to increased physical understanding and improved modeling of these and other climate variations.

For example, mixed layer properties (temperature, thickness and heat storage) influence climate over the ocean and adjacent land areas: Sea surface temperature anomalies in the tropical Atlantic Ocean are strongly correlated with rain over northeast Brazil (Nobre and Shukla 1996), the Caribbean and North America (Enfield and Alfaro 1999; Enfield et al. 2001), and the sub-Saharan region (Lamb and Peppler 1992). While sea surface temperature is an important parameter for understanding interactions between ocean and atmosphere, ocean heat storage also plays an important role: A thick layer of warm water supplies more energy than a thin one for hurricane intensification (e.g. Shay et al. 2000).

It was also recognized some time ago that ocean heat content could dominate temporal variability of the earth's heat budget (Rossby 1959). The possibility of a warming ocean due to increasing greenhouse gasses has also been posited for some time (White House 1965), as has the potential for delay of greenhouse-gas induced atmospheric warming due to initial uptake of heat by the world ocean (National Research Council 1979). Ocean heat content estimates and analyses (e.g. Levitus et al. 2000, 2001, 2005a, b) have supported these hypotheses, helped to verify climate models simulating greenhouse-gas induced warming (e.g. Barnett et al. 2001, 2005; Hansen et al. 2005), and have the potential to improve their predictive skill. Ocean heat content is thus a critical variable for monitoring earth's climate system and for detection and attribution of climate change due to the observed increase of greenhouse gases in earth's atmosphere.

Ocean salinity is very important dynamically on a variety of time-scales; for instance, a freshwater cap in the northernmost Atlantic Ocean could reduce the ocean's meridional overturning circulation, greatly affecting the weather of nearby continents (Curry and Mauritzen 2005). In addition, changes in ocean salinity distributions are sensitive indicators of climate variations, allowing tests of climate models (Banks and Woods 2002) In situ salinity measurements are at present insufficient to allow a reasonably certain discussion of interannual upper ocean freshwater content variability globally for 2005. In many locations the historical record may be insufficient to define an ocean salinity climatology, much less analyze interannual variations around that climatology, although linear trends have been computed as a function of latitude alone from 1955 – 1998 in the major ocean basins (Boyer et al. 2005). More detailed regional analyses of interdecadal, and in some cases interannual, ocean salinity variations are possible in better-sampled areas of the ocean like the North Atlantic Ocean (e. g. Curry and Mauritzen 2005) or with oceanographic cruises repeatedly occupied in more remote areas such as the South Indian Ocean (e.g. Bryden et al. 2003). These analyses are usually a few years out of date because there is still a significant time delay in availability of climate-quality ocean salinity data.

However, the Argo Project (Roemmich et al. 2004;

http://www.argo.net/) array of profiling CTD (Conductivity-Temperature-Depth) floats began in 2000 and will allow estimates of global freshwater content variability. It first achieved sparse global coverage in 2004 and is expected to achieve global coverage at its target density within the next few years. When complete, this array will collect temperature and salinity profiles from 2000 m to the surface at 10-day intervals from about 3000 floats spaced roughly every 3 degrees of longitude and latitude throughout the ice-free global ocean. In a few years sufficient salinity data will be collected to allow construction of a robust mean climatology and seasonal cycle (where there is a seasonal cycle in salinity).

Here we focus primarily on upper ocean heat content variability. Ocean transport variations are discussed in another section of this document. Analyses of ocean heat content have traditionally relied solely on in situ data from instruments such as mechanical and expendable bathythermographs (MBTs and XBTs), Conductivity Temperature Depth (CTD) profilers, thermistors on moorings, surface drifters, and more recently, CTD equipped profiling floats and bathythermograph equipped pinnipeds. In situ data, while arguably sparse in space and time with respect to natural variability (Gregory et al. 2004), have been used to generate annual estimates of upper ocean heat content (from 0 – 700 m) throughout the global ocean on annual time scales. Pentadal estimates to greater (0 – 3000 m) depth have also been generated (Levitus et al. 2005a, b), showing an overall warming trend of the ocean from 1955 through 2003. These results are reviewed below. Monthly Atlantic mixed layer properties estimated from in situ data are also analyzed from 1997 through November 2005 in regions where data coverage is sufficient.

In situ estimates of ocean heat content (calculated from the data source mentioned above as anomolies with respect to an ocean temperature climatology) have tended to be sparsely sampled in space and time. Starting in 1993, sea surface height anomalies (SSHA) maps from satellite altimetry (http://www.aviso.oceanobs.com/) provide more complete temporal and spatial coverage of the ocean surface over much of the globe. Because SSHA fields are dynamically related to ocean heat content anomaly (OHCA) fields, satellite-based OHCA fields can be generated by calculating local regressions of in situ upper (0 – 750 m) OHCA data against SSHA data, and then applying these coefficients to the SSHA maps. The OHCA maps derived from SSHA can then be used to fill in areas and times where no in situ OHCA estimates exists. Thus annual OHCA maps can be generated almost globally, even in areas where the density of in situ observations is small (Willis et al. 2003, 2004). Over larger spatial scales and longer time scales, changes in the ocean mass measured by the altimeter likely contaminate SSHA-based OHCA estimates. On regional scales, salinity variability may also contaminate such estimates, because both salinity and temperature affect ocean density, and thus ocean sea surface height. However, maps of OHCA made by combining in situ data with SSHA maps have greater accuracy than OHCA estimates from in situ data alone, especially when and where those in situ data are sparse. Below we update combined OHCA estimates of Willis et al. (2004) using in situ data and satellite altimetry maps collected and generated, respectively, through the end of October 2005. We also discuss how in situ sampling variability affects the temporal and spatial structure of error estimates for in situ OHCA maps.

Global in Situ Ocean Heat Content Anomaly Estimates

Yearly global upper (0 – 700 m) OHCA estimates for 1955 – 2003 and deeper (0 – 3000 m) pentadal (5-year) OHCA estimates for 1955 – 1959 through 1994 – 1998 (Fig. 1; Levitus et al. 2005a, b) are based on approximately seven million historical and modern temperature profiles that have become available as part of the *World Ocean Database 2001* (Conkright et al. 2002). In addition, approximately 310,000 additional temperature profiles that became available since the release of WOD01 have also been used in this analysis. Many of the recent data used represent real-time and delayed-mode data reported via the IOC Global Temperature Salinity Profile Project (IOC 1998). Many of the historical temperature data that have made these estimates possible have been recovered as part of “data archaeology and rescue” projects (Levitus et al. 2005c).

A large part of the total change in ocean heat content during the past 50 years occurred in the upper 700 m of the world ocean (Fig. 1). The difference between the 0 –700 m and 0 – 3000 m curves at the beginning of the record is likely owing to the lack of data for the yearly as compared to the pentadal compositing periods. Both time-series show similar variability. For the world ocean the linear trend of heat content (for the 0-3000 m layer for 1955-98) is 0.33×10^{22} J $year^{-1}$, corresponding to a rate of 0.2 W m^{-2} (per unit area of the earth’s total surface), and the overall increase in heat content for the world ocean is 14.5×10^{22} J. The ocean warming is estimated to be about 84% of the total global warming since 1955 (Levitus et al. 2005b).

A large decrease in global ocean heat content is evident beginning around 1980 (Fig. 1). The 0 – 700 m layer

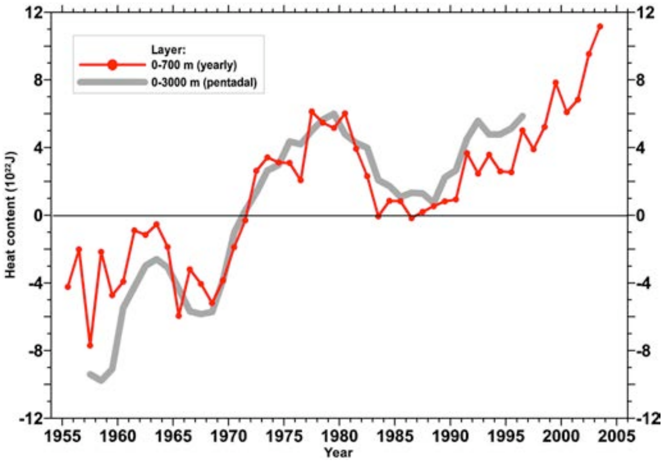

Figure 1. Time series of annual average global upper (0 – 700 m, red line with dots) Ocean Heat Content Anomaly (OHCA; J) estimated and deeper (0 – 3000 m, thick grey line) pentadal (5-year) global OHCA estimates for 1955 – 59 through 1994 – 98 from Levitus et al. (2005a). Annual and pentadal estimates are plotted at their temporal mid-points.

exhibits a decrease of approximately 5.8×10^{22} J between 1980 and 1983, corresponding to a cooling rate of 1.2 W m^{-2} (per unit area of the earth's total surface). Most of this decrease occurs in the Pacific Ocean and may be associated with a sign change of the Pacific Decadal Oscillation (Stephens et al. 2001; Levitus et al. 2005a, b). Estimates of ocean heat content changes for 1994 – 2003 (Willis et al. 2004) are in rough agreement with net radiation at the top-of-the-atmosphere, available only since 1985 (Wong et al. 2006). This agreement includes interannual variability of approximately 1.5 W m^{-2} (per unit area of the earth's total surface) associated with the 1997 – 98 El Niño. El Niño and the Pacific Decadal Oscillation appear linked (Zhang et al. 1997), leading to the suggestion that processes which may lead to changes in the net radiation at the top of the atmosphere associated with El Niño may have an analogue in the Pacific Decadal Oscillation, and the further suggestion that these processes are due to internal variability of the ocean-atmosphere system.

Global Combined in Situ and Altimeter Ocean Heat Content Estimates

We (JML, JKW, and GCJ) have also updated the in situ ocean temperature data and satellite altimetry maps that start in 1993 through 31 October 2005. We have used these in situ data and maps to produce annual average maps at quarterly intervals from 1993.5 through 2005.5 of upper (0 – 750 m) OHCA relative to a ten-year 1993 – 2002 baseline using the Willis et al. (2004) methodology. Maps of OHCA can be produced from the satellite data alone, the in situ data alone, and the two data sets combined. Here we will focus on the combined estimates only.

Since each OHCA map is normally based on a year's worth of data, the 2005.5 maps are suboptimal because at the time they were produced we were missing 2 months of data. In addition, the satellite only and combined OHCA maps for 2004.75 – 2005.25 are also suboptimal because only preliminary real-time satellite altimeter maps were available for dates after 7 January 2005 at the time of the analysis. Thus, maps during these periods use at least some real-time satellite data. Maps of OHCA for the last few years will be improved in the future by use of finalized satellite altimeter data and inclusion of more in situ data as profiles taken in the field but not yet publicly available are gradually reported to, gathered by, and made available from oceanographic data centers.

Because of differences in processing of the real-time and delayed mode altimeter data, these preliminary maps may not be optimal for looking at subtle (equivalent to order 1 W m^{-2}) global average OHCA variations (e.g. Willis et al. 2004; Levitus et al. 2005a,b). In addition, the Argo Project profiling CTD float array has significantly changed ocean sampling. First, floats sample at even 10-day intervals, whereas shipboard data sample more sporadically with potential seasonal biases. Second, the floats are distributed globally, whereas shipboard data are concentrated along shipping routes that miss wide swaths of the ocean. The effects of real-time altimetry on the maps and the change of in situ sampling patterns over the last few years preclude updating the combined estimate of globally averaged OHCA through the end of 2005 at this time. This curve will be updated as soon as delayed-mode altimeter data becomes available and any effects due to the new sampling regime can be more fully explored. However, local variations of the combined OHCA maps over interannual and even decadal time-scales are analyzed here because they are much larger than potential artifacts owing to sampling changes.

The 2005.5 combined OHCA map compared to a 1993 – 2002 baseline (Fig. 2, top) shows eddy and meander variability down to the 100-km mapping scales. Some large-scale patterns are also evident. OHCA is high in the subpolar N. Atlantic and low in the subtropical N.

Atlantic, consistent with a decreased strength of the North Atlantic Current. This pattern is probably related

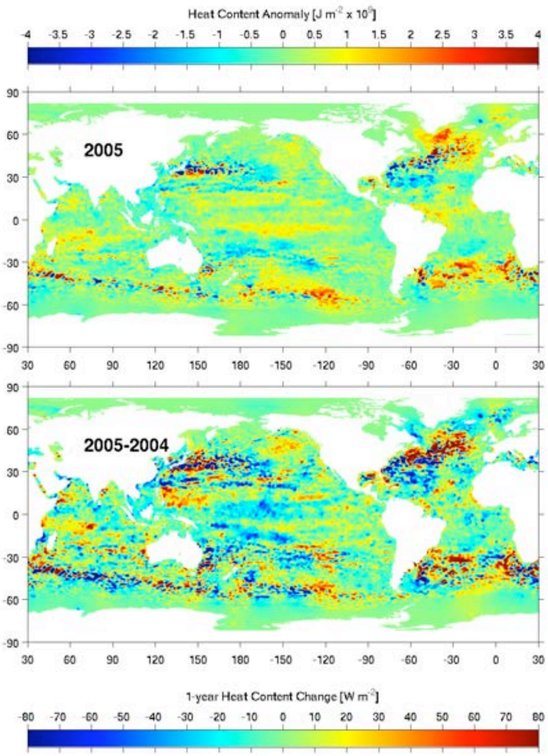

Figure 2. The 2005.5 satellite and in situ upper ocean (0 – 750 m) combined OHCA map following Willis et al. (2004) relative to a 1993 – 2002 baseline period (top; J m^{-2}) and the difference of the 2005.5 and 2004.5 combined OHCA maps (bottom) expressed as a surface heat flux equivalent (W m^{-2}).

to decadal changes in the North Atlantic Oscillation (e. g. Curry and McCartney 2001). This climate index was lower in 2005 than during the baseline period of 1993-2002, and has trended lower from 1993 through 2005. The tropics in 2005 have generally higher OHCA than for the baseline period, but not excessively so, reflecting the lack of an El Niño or La Niña in 2005. In 2005 OHCA is high throughout the South Pacific and South Atlantic Oceans in a belt located north of the Antarctic Circumpolar Current. There is a large amount of small-scale spatial variability associated with this current and the western boundary currents.

The difference in combined OHCA maps between 2005.5 and 2004.5 (Fig. 2, bottom) illustrates the large year-to-year variability in ocean heat storage, with changes reaching or exceeding the equivalent of an 80 W m^{-2} magnitude surface flux over a year in many places. Comparison with the global averaged absorption of solar radiation by the ocean and atmosphere of about 238 W m^{-2}, these variations are quite substantial. Ocean advection likely plays a large role in many of these changes. This difference between two years clearly shows the influence of eddies and meanders, as well as the larger scale patterns discussed above in the subtropical and subpolar regions. The decrease in OHCA in the central equatorial Pacific between 2005 and 2004 probably reflects the transition from a very weak El Niño to more normal conditions. Also of interest, given the strong 2005 hurricane season and the potential link between hurricane intensity and warm ocean waters (e.g. Shay et al. 2000; Emanuel 2005; Webster et al. 2004) are the large increases in OHCA around Florida and the Gulf of Mexico from 2004 to 2005.

Eddies and meanders are mostly absent from the 13-year linear trends in the combined OHCA maps (Fig. 3, top), since such features are smoothed out over decadal time-scales. The amplitudes of the decadal changes are smaller than the year-to-year changes by nearly an order of magnitude. Assuming every year is statistically independent and accurately estimated, the linear trends exceed the 95% confidence intervals in only a few locations (Fig. 3, bottom). Notable changes in OHCA include a strong increase in the subpolar N. Atlantic already discussed above. In addition, there is strong decrease in the subpolar N. Pacific that may be related to changes in the wind field (Qiu 2002; Cummins and Lagerloef 2004) likely associated with the Pacific Decadal Oscillation. Also interesting and apparently significant are the increases in OHCA in the southern Hemisphere, north of the Antarctic Circumpolar Current. This change has recently been studied in the South Pacific (Roemmich et al. 2006) and related to changes in the wind-stress field associated with an increase in the Antarctic Oscillation. Increases in OHCA in the southern hemisphere subtropical gyres in all three oceans may be related. Decadal changes in the tropics are mostly not significant, which is not surprising given the large amplitude of interannual variability and the relative shortness of the 13-year record.

Global Uncertainty Estimates and Sampling Metrics

We (JML, JKW, and GCJ) are expanding and improving the error analysis for the Willis et al. (2004) methodology. Previously, only the uncertainty of the trend in global average combined OHCA over the entire period studied was estimated. In reality, errors change with each in situ and combined map as in situ sampling distributions vary (while remaining relatively constant for the satellite only map). We are presently working on systematically propagating all significant sources of uncertainty (including in situ sampling distributions, the seasonal cycle, instrument noise, and the model for combining in situ heat content and satellite altimetry) through the estimates.

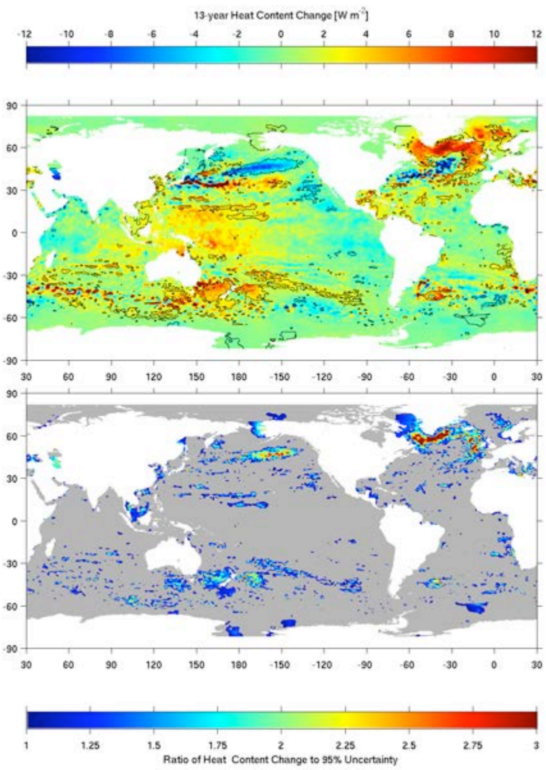

Figure 3. Linear trends in heat content change from combined OHCA maps 1993 – 2005 (top) expressed as a surface heat flux equivalent (W m^{-2}) with areas of significant slope outlined in black as estimated by the ratio of these trends to their 95% uncertainty estimates (bottom, where colored regions are increasingly significantly different from zero but grey are not).

As an illustration, we discuss the effect of year-to-year variations in the in-situ data sampling distribution on the uncertainties in the annual global averaged in situ OHCA estimates. Although this is just one of several terms that must be taken into account in the total uncertainty of the combined OHCA estimates, it may be the dominant one.

While satellite altimetry provides relatively complete nearly global coverage of SSHA, in situ data distributions can be sparser than optimal for estimating OHCA globally. Estimates of the annual 95% uncertainty in OHCA are made by sub-sampling every year of the 13-year record of SSHA in the same manner as the in situ sampling pattern for a given year. To derive the uncertainties, the global integral of SSHA, for the 13-year record, is constructed from maps of sub-sampled data set (Willis et al. 2004) and compared to the global integral of SSHA based on the complete SSHA maps. The uncertainty of the global mean in SSHA (Willis et al. 2004) must be added in quadrature to these uncertainties to account for unsampled geophysical variability. Then the SSHA uncertainty can be converted into an OHCA uncertainty using a global regression coefficient betwee the two quantities.

The contribution of this error source to the global averaged in situ estimate varies significantly from year

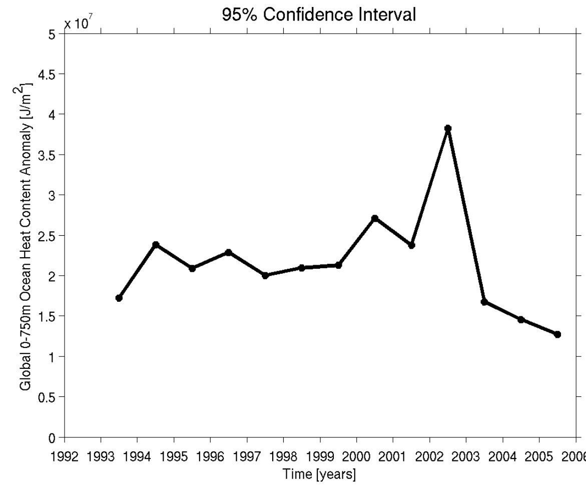

Figure 4. In situ annual global mean OHCA uncertainty from 1993 – 2005, estimated as discussed in the text. The sharp decrease in 2003 – 2005 is owed in large part to the growth of the Argo Project.

to year (Fig. 4). Most notably, while 2002 and 2005 globally averaged in situ only OHCA estimates make use of a similar number of temperature profiles (about 150,000 in each year), the 2005 estimate has a much smaller sampling uncertainty than the 2002 estimate. This change results because the Argo Project global array of profiling CTD floats grew dramatically from about 400 floats near the start of 2002 to about 2200 floats near the end of 2005, resulting in a more widespread sampling spatially and more uniform sampling temporally in 2005 than previous years. There may still be a lag of several years for non-Argo in situ data (such as ship-based XBT and CTD profiles) to make their way to the public archives we are using. In that case this component of uncertainty for subsequent analyses that include additional in situ data could be further reduced.

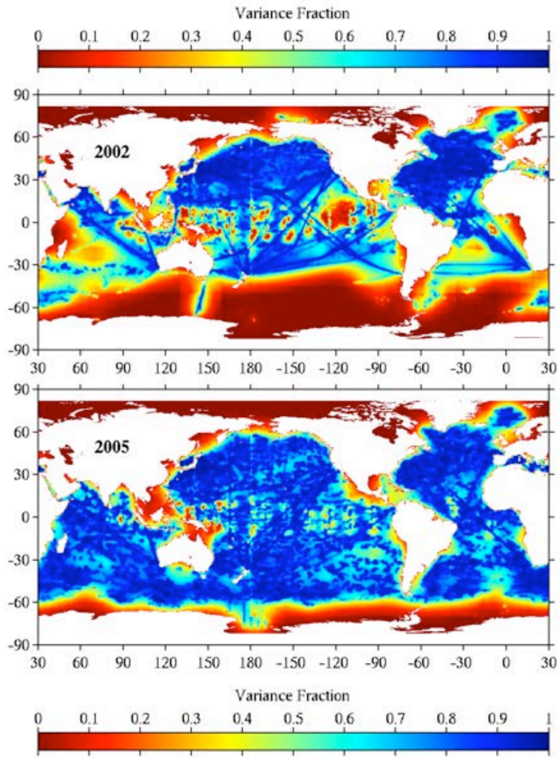

Figure 5. Energy of a global unit OHCA mapped with in situ sampling patterns for 2002 (top) and 2005 (bottom), a much better sampled year with the advent of the global Argo Project array of profiling CTD floats. Fields result from the sampling pattern and the geophysical mapping parameters from Willis et al. (2004), with 1 being very well sampled, and 0 being unsampled.

For each year's sampling pattern, we can map (e.g . Fig. 5) where the ocean sampling is good (approaching 1) and where it is poor (approaching 0). These maps for 2002 and 2005 (Fig. 5) reveal the reason that the in situ error for the global average OHCA in 2002 is larger than in 2005. In 2002 large swaths of the southern hemisphere, and other regions are badly undersampled. However, by 2005, the growing Argo Project array of profiling CTD floats is doing a much better job at sampling OHCA for the global ice-free ocean.

Monthly Atlantic Mixed Layer Properties from in situ Data for 1997 to 2005.

The ocean mixed layer is the portion of the ocean that interacts directly with the atmosphere. The temperature and thickness of this layer have wide-ranging importance in climate studies, from ocean-atmosphere carbon exchange to hurricane intensification. Here we (CS) analyze seasonal to interannual variability of mixed layer temperature and thickness in select Atlantic regions with sufficient data coverage using preliminary in situ data from 1997 through November 2005. Irregularly spaced in situ data are mapped to a uniform grid using a standard objective analysis technique that takes into account error energy as well as spatial and temporal scales of variability. Data coverage is best in the tropical Atlantic and the subtropical North Atlantic (Fig. 6). The data set for 2005 is not complete so annual means for 2003 and 2004 are compared. Large regions in the tropical Atlantic and the subtropical North Atlantic have sufficient data coverage (best centered near 30˚N) for comparisons in these years (Fig. 7). Monthly estimates for select regions over the full time period are also discussed.

The 2003 annual average temperature (not shown) looks quite similar to that for 2004 (Fig. 8, top left) mainly due to the large temperature range that masks differences an order of magnitude smaller. The difference between 2003 and 2004 (Fig. 8, top right) reveals about 1˚C higher temperatures around 5˚N, near 45˚W and 20˚W, in 2003. In the western equatorial region, temperature differences alternate in sign (positive near S. America, negative farther east). Northeast of the Bahamas the water is colder in 2004, whereas it is warmer farther east. Areas such as the eastern equatorial band have insufficent observations for comparison. Similarly, the colder water to the north, at about 15˚N, 35˚W is only based on few observations in both years. All differences south of about 25˚S may also be an artifact of much poorer local sampling in 2003 (Fig. 7).

Mixed layer thickness differences are about 10 m in regions with sufficient data coverage (Fig. 8, bottom right). Along 5˚N the mixed layer in the western basin is about 10 m thicker (positive difference) in 2004, whereas it is about 10 m thinner in the eastern basin. On the equator the mixed layer is thinner in 2004. Around 30˚N a region of negative differences is south of a region with positive differences. Here mixed layer heat storage differences (not shown; on the order of 10^9 Jm^{-2}) are very closely related to mixed layer thickness differences.

As noted above, sea surface temperature anomalies over the tropical North and South Atlantic have significant climate impacts over adjacent land masses. Here well-sampled subregions of the tropical North and South Atlantic are analyzed, so the tropical North Atlantic (TNA) is defined as 13 – 16˚N, 40 – 30˚W and the tropical South Atlantic (TSA) as 6˚S – 0, 30 –22˚W (Fig. 6, small rectangles). In the TNA monthly data

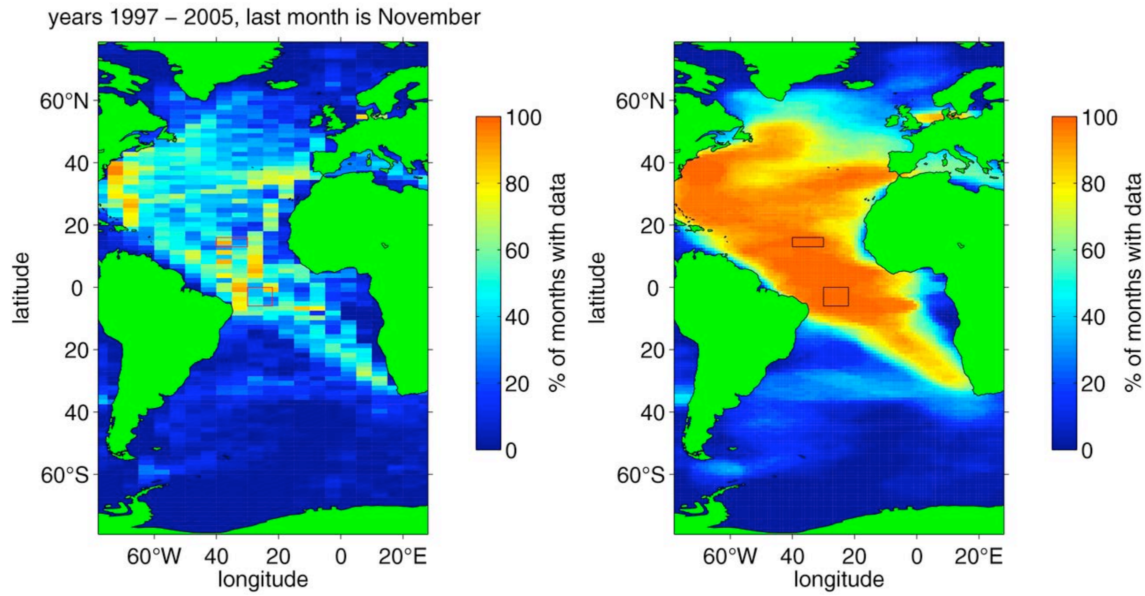

Figure 6. Data coverage for January 1997 - November 2005. Raw percentage of months with observations (left). Red rectangles indicate subregions of the tropical North and South Atlantic. Percentage of months with observations after objective analysis was used to interpolate the data for every month onto a regular grid before the data coverage was derived (right). Black rectangles indicate subregions of the tropical North and South Atlantic.

coverage varies between 25 and 100% and exceeds, on average 50%. In the TSA monthly data coverage is a little lower but the average is about 50%. In both regions the data coverage after objective analysis is 100% in most months and almost always exceeds 80%. This apparent increase in coverge occurs because the analysis smooths and interpolates data given the spatial and temporal scales of geophysical variability.

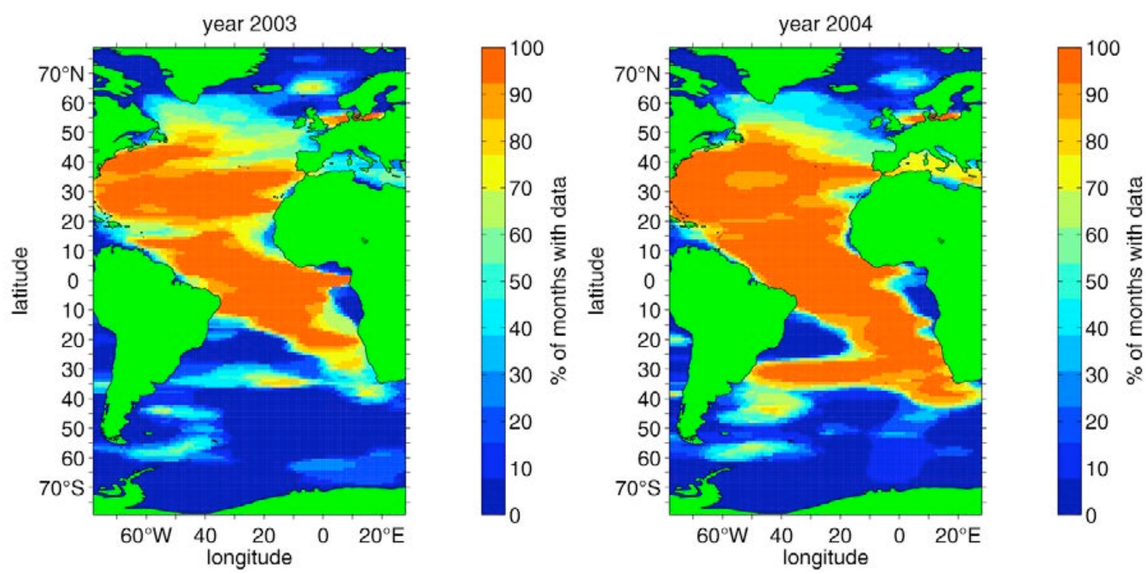

Figure 7. Data coverage, after objective mapping, for 2003 (left) and 2004 (right).

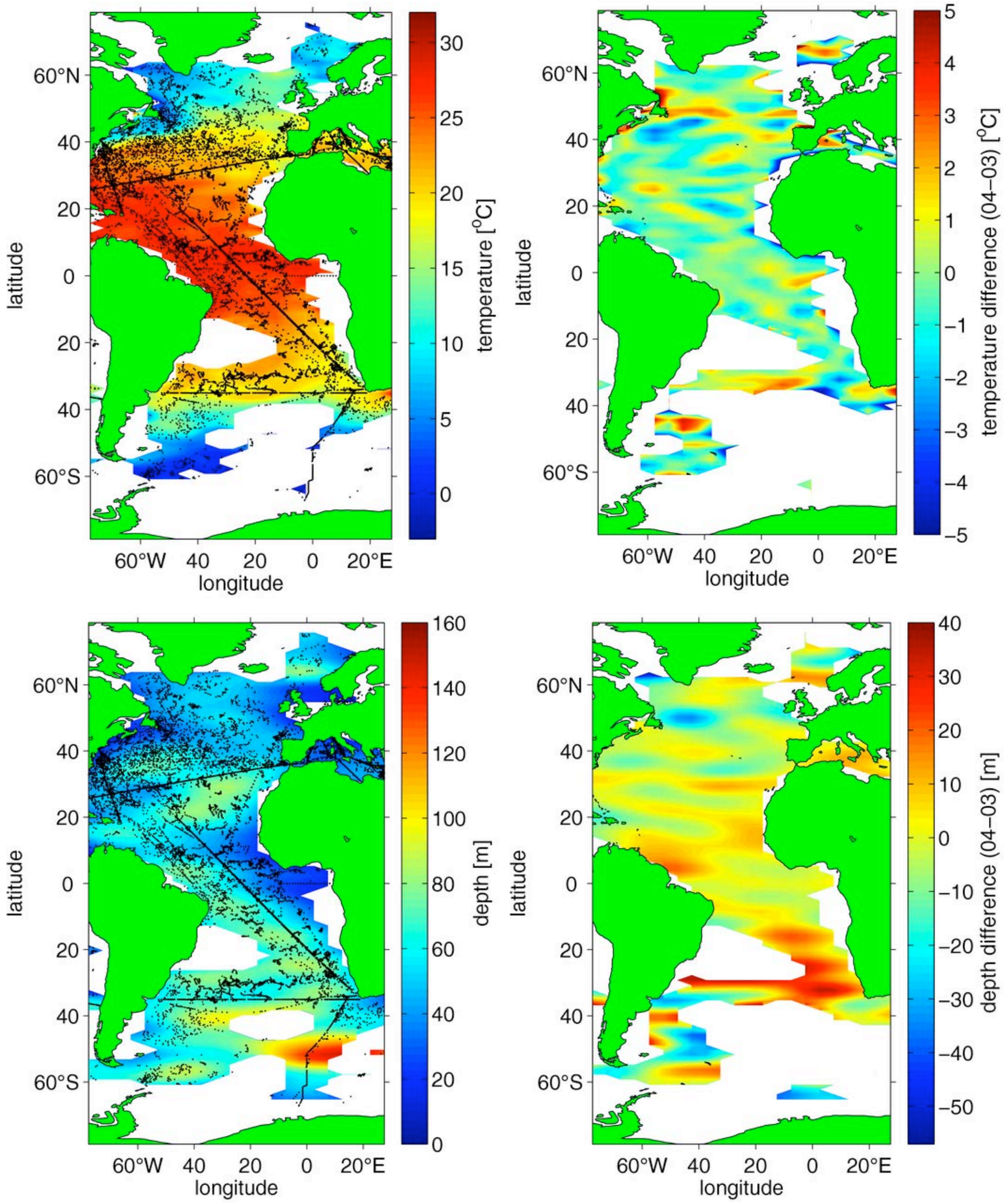

Figure 8. Annual mean mixed layer temperature (top left) and thickness (bottom left) for 2004. Black dots indicate profile positions. Differences of the 2003 and 2004 annual mean mixed layer temperature (top right) and thickness (bottom right).

TNA mixed layer temperatures vary from 23.5 – 28 ˚C (Fig. 9, top left) with lows in February-April and the highs in September-November. Interannual temperature minimum variations are about 1 ˚C and temperature maximum variations do not exceed 0.8 ˚C. Relatively low maximum temperatures are found in 1999-2000. This period, also containing the lowest minimum temperatures, is coincident with strong La Niña conditions. Over the last 5 years (2001-2005) the interannual variability is quite small, and there have been no strong El Niño or La Niña conditions.

TNA mixed layer thickness varies between about 30 m in boreal fall and up to 80 m in boreal spring (Fig. 9,

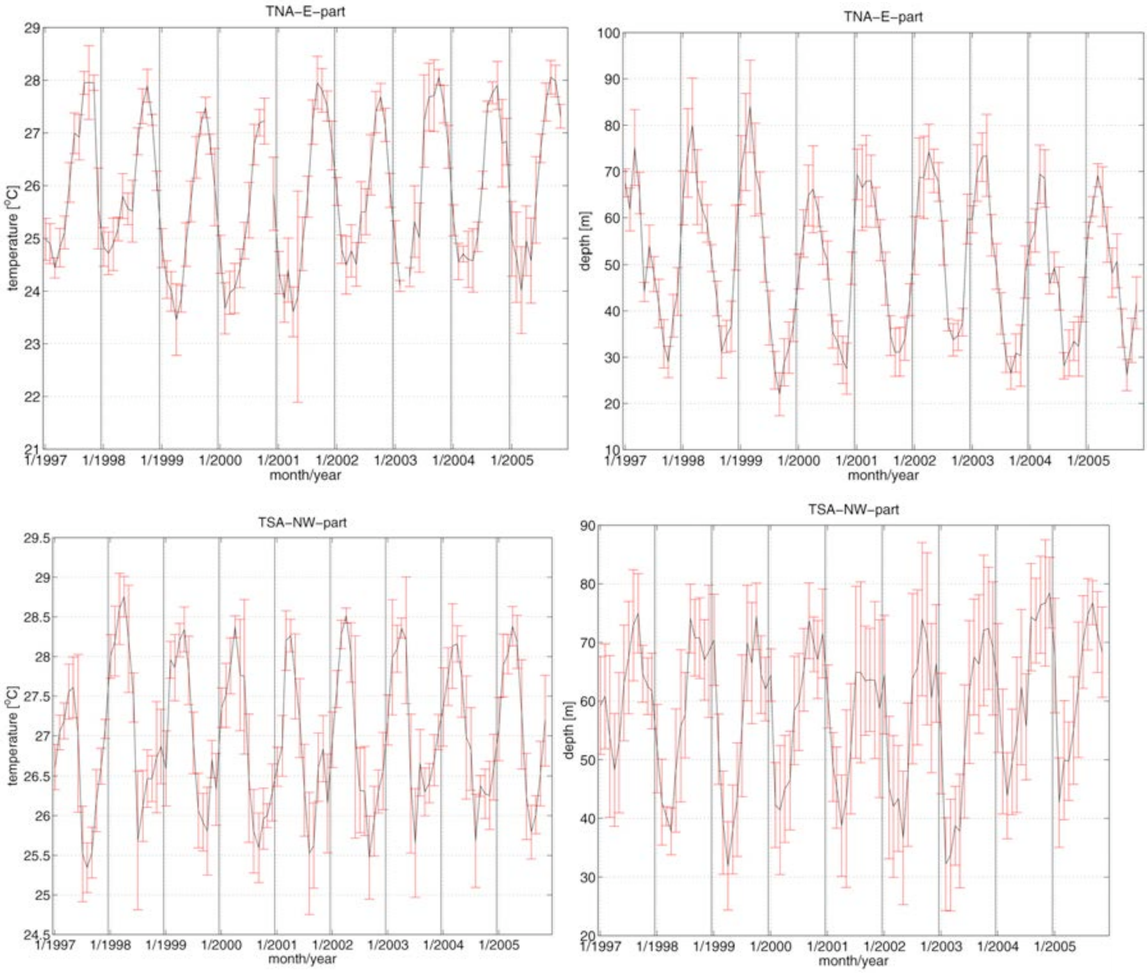

Figure 9. Time series of monthly mixed layer temperature (left, ˚C) and thickness (right, m) in the tropical North Atlantic (top; TNA; 13 – 16˚N, 40 – 30˚W) and the tropical South Atlantic (bottom; TSA; 6˚S – 0, 30 – 22˚W) with one standard deviation error bars.

top right). The highest maximum and lowest minimum occur in 1999, an exceptional year. The next year has the lowest maximum and an average minimum. Given the Strong 1997 – 98 El Niño and the 1999 – 2001 La Niña, a correlation between this climate variability and mixed layer thickness in this region seems unlikely**.** As for the temperature, interannual variability in the last 5 years is small. Mixed layer heat storage variations (not shown) correlated well with mixed layer thickness variations.

TSA mixed layer temperature (Fig. 9, bottom left) is roughly opposite in phase to TNA mixed layer temperature, with minima in austral fall and maximum in austral spring. However, the 25.5 – 28.5 ºC TSA temperature range is smaller than that in the TNA. From 1999 to 2005 interannual TSA variability is small. Satellite observations could be included to determine if the interannual variability at the beginning of the time series is owing to the sampling patterns.

As for the TNA, TSA mixed layer thickness (Fig. 9, bottom right) varies from 30 – 80 m, and is again a mirror image of the TNA in the sense that the TSA maxima occur in austral spring and the minima in austral fall. The thinnest mixed layers are in 1999 and 2003, and the thickest mixed layers are in 2004 and 2005, so a correlation with El Niño conditions is not evident. Again TSA heat storage (not shown) follows mixed layer thickness closely.

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Equatorial Pacific Ocean Variability (El Niño)

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A weak El Niño developed in the equatorial Pacific during the second half of 2004 and ended in March 2005. Anomalous warming was for the most part centered around the international date line, with near normal sea surface temperatures (SSTs) prevailing most of the time in the far eastern eastern Pacific and along the west coast of South America. SST anomalies in the NINO3.4 index region (5°N-5°S, 120°-170°W) were approximately 0.6°C on average from July 2004 to February 2005, with peak seasonal values of 0.8°C during August to December 2004. The Southern Oscillation Index (SOI), which is the normalized surface air pressure difference between Darwin, Australia, and Tahiti, French Polynesia, was on average –1.0 from July 2004 to February 2005. The trade winds were unusually weak west of the date line associated with the elevated central and western Pacific SSTs and negative SOI values throughout much of 2004 and early 2005. These oceanic and atmospheric anomalies were consistent with warm phase El Niño/Southern Oscillation (ENSO) conditions. The equatorial Pacific subsequently returned to near normal as surface wind, SST, and thermocline depth anomalies weakened after February 2005. Conditions remained near-normal until late in the year, when weak La Niña-like SST anomalies developed in the eastern Pacific and the trade winds became anomalously strong in the central and western Pacific (Fig. 1).

The 2004-05 El Niño was characterized by significant month-to-month variability in both the ocean and the atmosphere. The SOI for example was highly variable during the event, ranging from 0.3 in January 2005 to –4.1 in February 2005. The very low SOI value in Febuary 2005, the lowest since February 1983 during the 1982-83 El Niño, was associated with a category-5 tropical cyclone (Percy). Surface westerly wind anomalies near the equator during this storm were the strongest of any period in 2004-05 (Fig. 1). The

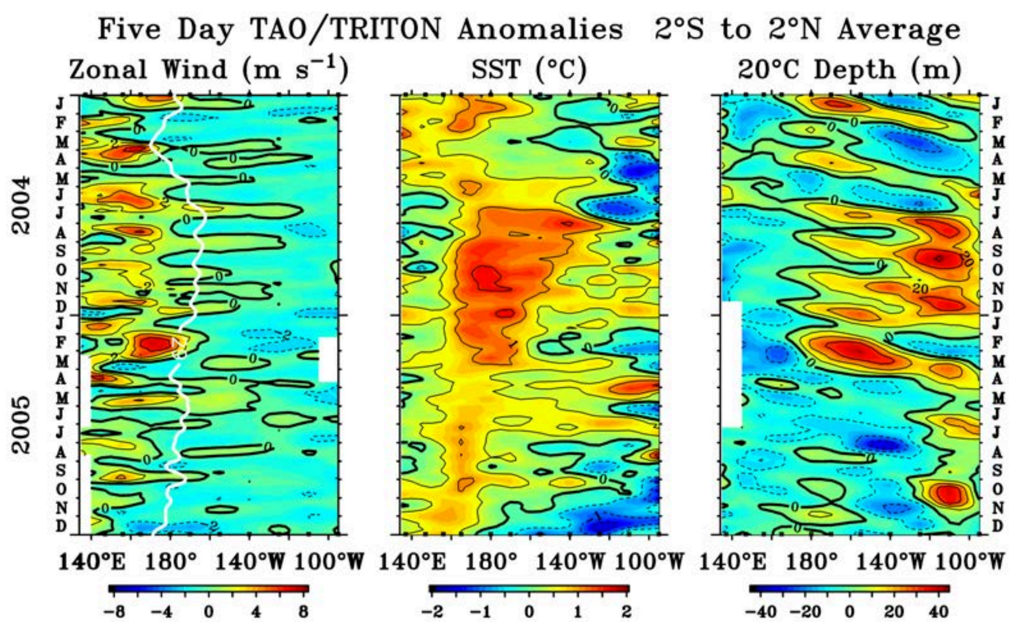

Fig. 1. Five-day average anomalies of zonal wind, SST, and 20°C depth (an index for the depth of the thermocline) relative to the mean seasonal cycle averaged 2°N–2°S based on TAO/TRITON moored time series data. White line on the zonal wind anomaly panel indicates the 29°C isotherms which marks the eastern edge of the western Pacific warm pool. Ticks on the horizontal axis indicate longitudes sampled at the start (top) and end (bottom) of record.

Madden-Julian Oscillation (MJO), initiated as convective flare-ups over the Indian Ocean and subsequently propagating eastward into the western Pacific, also contributed to the month to month variability in atmospheric and oceanic indices. The westerly phase of the MJO was linked to 2-3 week long westerly wind bursts in the western Pacific, which forced eastward propagating downwelling intraseasonal equatorial Kelvin waves. These waves deepened the thermocline in the eastern Pacific by 20-30 m and lead to warming of eastern Pacific SSTs, though this warming did not always persist beyond the passage of individual the Kelvin waves (Fig. 1).

An unusual feature of this event was that excess heat content along the equator, typically a precursor to subsequent ENSO SST anomaly development (Jin, 1997; Meinen and McPhaden, 2000), did not precede but rather developed in phase with NINO3.4 SST anomalies during 2004-05 (Fig. 2). The lack of a subsurface heat content precursor may account for the relative weakness of the 2004-05 El Niño and the difficulty in predicting its onset (Lyon and Barnston, 2005) since such precursors are indicative of large-scale deterministic processes controlling the evolution of ENSO. More prominent in relative terms was the influence of stochastic forcing associated with weather variability during the 2004-05 El Niño. The state of the climate report for 2004 (Levinson et al, 2005) provides additional information on the interplay between large-scale ocean-atmosphere dynamics and stochastic forcing during the onset and early evolution of the 2004-05 El Niño. By the end of 2005, the excess equatorial heat content prevalent during most 2004-05 had disappeared in association with the onset of cold La Niña conditions (Fig. 2).

During the 2004-05 El Niño, deep atmospheric convection was highly variable in the along the equator in the western and central Pacific, and persistent anomalous rainfall that characterizes mature warm phase ENSO conditions failed to develop near the date line except in February 2005. The relative absence of such persistent anomalous atmospheric convection indicated that the ocean and atmosphere were only weakly coupled during this event. As a result, the El Niño had only limited global climatic impacts. Those impacts included below normal rainfall in Indonesia, the Philippines, and portions of South Africa and Central America in the last quarter of 2004 and January 2005 (Lyon and Barnston, 2005). Likewise, the failure of persistent warm SST

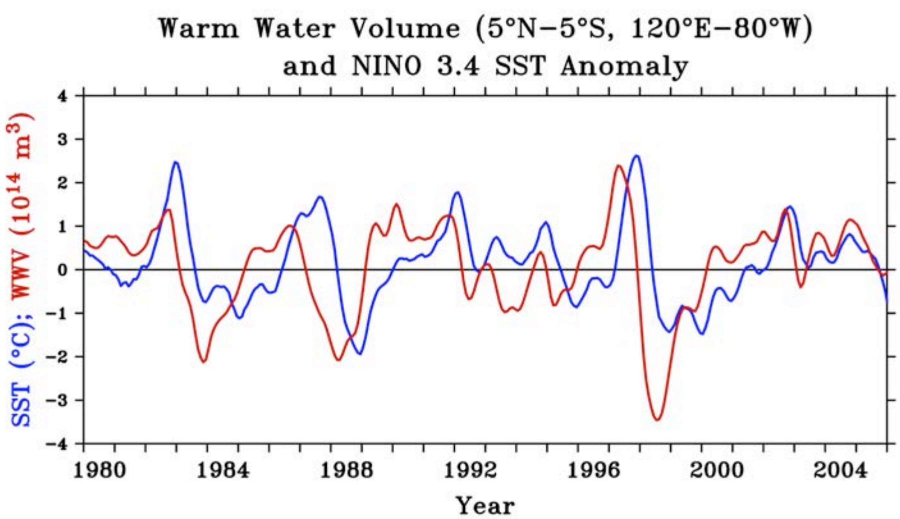

Fig. 2. Monthly anomalies of NINO3.4 SST and warm water volume (WWV) from January 1980 to December 2005. WWV, which is an index of heat content along the equator, is based on a blended thermal field analysis of TAO/TRITON moored time series data and ship-of-opportunity expendable bathythermograph (XBT) data integrated over the region 5°N–5°S, 80°W–120°E above the 20°C isotherm. NINO3.4 SST represents an average anomaly over the region 5°N–5°S, 120°W–170°W. Time series have been smoothed with a 5-month running mean filter for display.

anomalies to develop in the eastern equatorial Pacific and along the west coasts of the Americas limited the effects of this El Niño on marine ecosystems in those regions.

Weak warm SST anomalies in the equatorial Pacific, their concentration in the central basin, the weakness of equatorial ocean-atmosphere coupling, and the relatively muted impacts of Pacific SST anomalies on the global climate system lead to considerable controversy in the scientific community as to whether 2004-05 should be classified as an El Niño. Conditions in the Pacific met the definition for El Niño according to the criterion recently formulated by the National Centers for Environmental Prediction (NCEP), namely five consecutive overlapping 3-month seasons with NINO3.4 SST $\geq$ 0.5°C. However, this definition is not universally agreed upon, either because it is focused on a single region or defined only in terms of SST. Some putative impacts of this El Niño have likewise been actively debated, such as unusual dryness in the Pacific Northwest and extraordinarily rainy conditions in the Southwestern U.S. during boreal winter 2004-05.

The first two El Niños of the 21st century followed on the heels of a protracted, strong La Niña during 1998-2001, and were of moderate (2002-03) and weak (2004-05) intensity. This raises the question of whether the Pacific Decadal Oscillation (PDO) (Mantua et al, 1997) may be affecting the ENSO cycle. It has been argued (e.g. Peterson and Schwing, 2003) that the PDO shifted phase from positive to negative in the late 1990s, with the negative phase characterized by stronger than normal trade winds and colder than normal equatorial cold tongue SSTs. These conditions, which would favor weaker El Niño SST anomalies, have been observed in the tropical Pacific on average since the late 1990s (McPhaden and Zhang, 2004). Thus, a decadal change in background state may have contributed to the weakness of the 2004-05 El Niño, though the details of how ENSO and the PDO may interact with one another are not well understood at present.

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Arctic Ocean and Sea Ice

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Introduction

The permanent presence of sea ice is a unique feature of the polar oceans. The Arctic is further distinguished because it sustains a human population in a harsh environment. These characteristics amplify the impact of global climate change on both the regional physical and societal systems. These impacts reach beyond the Arctic region. For instance, studies are underway to determine the extent to which the loss of sea ice cover over the last two decades has impacted multi-year persistence in the surface temperature fields, especially in the Pacific sector.

In this report we provide observations that indicate continuing trends in the current state of physical components of the Arctic system, including the ocean and sea ice cover. The temporal extent of the data provides a multi-decadal prospective and confirms the sensitivity of the Arctic to changes in the global climate system. The destabilization of several known relationships between climate indices (e.g. Arctic Oscillation (AO)) and Arctic physical system characteristics (e.g. continued reduced state of the sea ice cover) presents an intriguing and significant puzzle with respect to the contemporary global climate system.

Ocean Circulation

Data from satellites and drifting buoys indicate that the circulation of the ocean surface layer has been characterized by an anticyclonic regime for the entire 2000-2005 period (Figure 1, top panel). The anticyclonic regime is the result of a higher sea level atmospheric pressure over the Arctic Ocean, relative to the 1948-2005 mean, and the prevalence of anticyclonic winds. The dominance of the anticyclonic circulation regime of the ocean surface layer is consistent with the AO index which has exhibited relatively low and fluctuating values since 1996 (Figure 2).

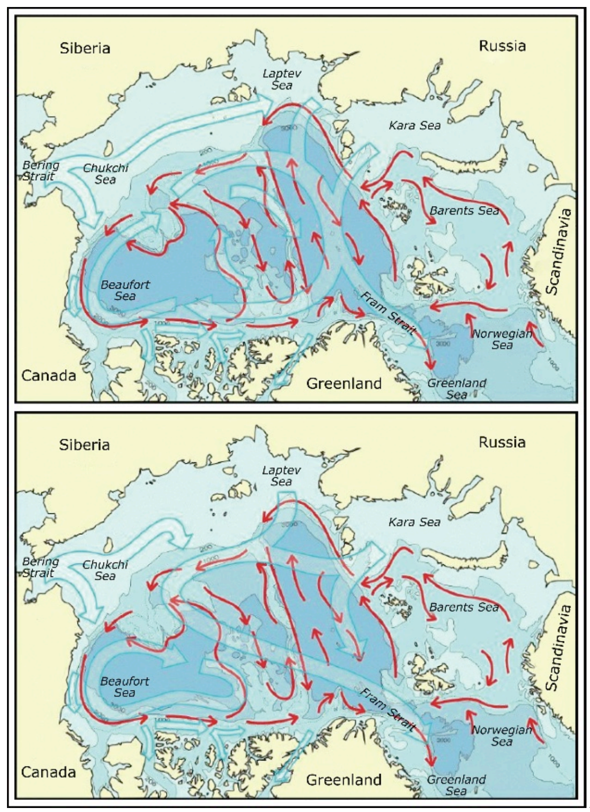

Figure 1. Idealized patterns of the dominant circulation regimes of the Arctic Ocean. Two circulation regimes of surface waters (anticyclonic – top, and cyclonic – bottom) are shown in wide blue arrows. In the cyclonic regime the clockwise circulation pattern in the Beaufort Sea region (Beaufort Gyre) weakens and the flow across the basin, from the Siberian and Russian coasts to the Fram Strait (Transpolar Drift), shifts poleward. The cyclonic pattern dominated during 1989-1996; the anticyclonic pattern has prevailed from 1997-present. The Atlantic water circulates cyclonically (red arrows) at approximately 200-800 m depth, independent of the circulation of the surface layer. (Adapted from Proshutinsky et al., 2005)

Climatological studies (e.g. Proshutinsky and Johnson, 1997) provide a foundation for understanding the significance of these ocean surface conditions. These studies indicate that the Arctic atmosphere and ocean surface layer motion alternates between cyclonic and anticyclonic circulation regimes, with each regime persisting from 4 to 8 years and resulting in a period of 8-16 years. Figure 1 illustrates idealized patterns of the two dominant wind-driven circulation regimes: anticyclonic and cyclonic. The cyclonic pattern dominated during the period 1989-1996 and the anticyclonic pattern has prevailed from 1997-present. Identification of the current or prediction of the future circulation regime is important because each regime is characterized by a set of environmental parameters that impact human activity in the Arctic. Atmospheric, ice and oceanic observational data, along with the results of numerical coupled ice-ocean models, provide evidence that during anticyclonic circulation regimes, compared to the cyclonic regimes, the arctic atmospheric pressure is higher, wind speed is lower, winter temperatures are colder, ocean waters are fresher, sea ice areal coverage is greater, and sea ice is thicker. When the cyclonic circulation regime dominates, the transport of sea ice from the Arctic Ocean increases, summer wind divergence produces more openings in the sea ice, allowing the upper ocean to accumulate heat. In addition, under a cyclonic circulation regime advection of heat with air masses to the Arctic also increases. This positive heat anomaly extends the ice melt season and leads to generally thinner ice. This description of oceanic and atmospheric conditions is consistent with environmental characteristics described by Thompson and Wallace (1998), who introduced the AO index. Figure 2 shows that during 2000-2005, the AO index fluctuated between positive and negative values and, on average, was relatively low. These recent characteristics correspond to the mean climatology, typified by a cold arctic and anticyclonic circulation regime as seen in Figure 2 prior to 1989.

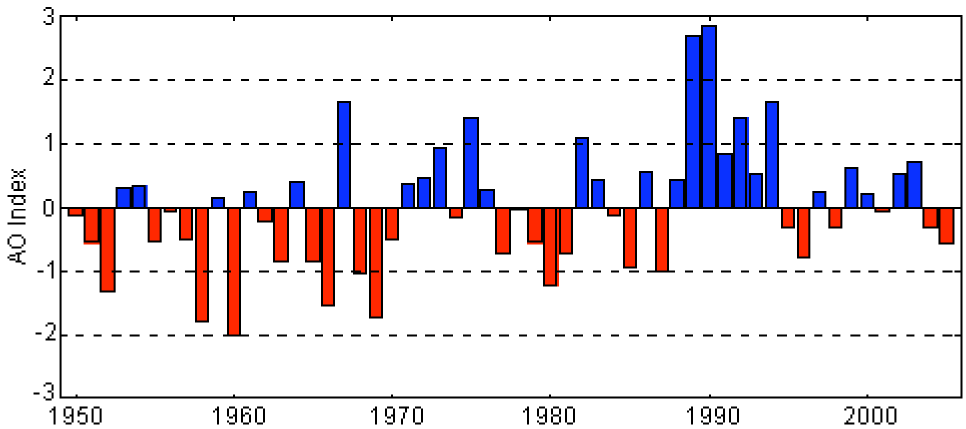

Figure 2. Time series of the annually-averaged Arctic Oscillation Index (AO) for the period 1950 – 2005, based on data from the website www.cpc.ncep.noaa.gov.

The circulation of Pacific water (located at the depths between 50 and 200 m) in the Arctic Ocean may be coherent with the surface currents but its pathways are not known from direct observations. Recently the vertical structure of this layer and its properties have been revised by Shimada et al. (2001) and Steele et al. (2004), where the presence of two types of summer Pacific halocline water and one type of winter Pacific halocline water in the Arctic Ocean were reported. According to the Environmental Working Group (EWG) analysis (EWG, 1997), the total thickness of the Pacific layer is approximately 150 m. This thickness is subject to temporal variability (McLaughlin et al., 2003) depending on wind stresses and circulation modes (Proshutinsky et al., 2002). Steele et al. (2004) found similar evidence in their examination of data from the 1980s and 1990s. The most recent studies by Shimada et al. (2006) and Maslowski (2006) speculate that the significant reduction of sea ice in the Canadian Basin observed in 2002-2005 (see Figure 10) is due to an increase of heat flux from the Pacific water layer to the bottom of sea ice which resulted in sea ice melt. Warming of the Pacific water is associated with the increase of heat flux via Bering Strait. In this region, preliminary observations from a mooring site, established and maintained since 1990, suggest that that annual mean water temperatures have been about a degree warmer since 2002, compared to 1990-2001(Woodgate, Aagaard and Weingartner, pers.comm., 2006). Since 2001, there has also been an increase in the annual mean water transport. Changes in the Pacific water circulation may also influence heat release from the Pacific water to the upper ocean layers.

The Atlantic water circulates in the Arctic Ocean at approximately 200-800 m depth. This water penetrates to the Arctic via Fram Strait and St. Anna Trough (Barents Sea). Under extensive surface cooling it sinks to intermediate depths and forms the warm Atlantic Layer with water temperature greater than 0°C. This layer is covered by low density surface waters and is thus prevented from undergoing heat exchange with the atmosphere. The most widely-accepted circulation scheme of

Atlantic water (Rudels et al., 1994) postulates that it circulates counterclockwise, forming several loops (Figure 1, red arrows) in the Arctic basins. Variability of the Atlantic water circulation pattern is not known from observations but model results show that its circulation has a pulsating character expressed in the propagation of warm and cold events, changing from seasonal to decadal time scales. An increase of the Atlantic water temperature in the Fram Strait and the Laptev Sea was observed in 2004 (Polyakov et al., 2005).

Heat and freshwater content

The heat and freshwater content of the Arctic Ocean are important integrated parameters and are indicative of the potential role of the Arctic Ocean in the global climate system. For example, the meridional overturning circulation in the Atlantic Ocean, an important component of the global ocean circulation, is significantly influenced by freshwater fluxes from the Arctic Ocean. It is suggested that the Arctic Ocean accumulates fresh water during anticyclonic circulation regimes and releases this water to the North Atlantic during cyclonic circulation regimes. The Beaufort Gyre (illustrated in Figure 1 by the closed clockwise circulation pattern in the Beaufort Sea region) is the major reservoir of fresh water in the Arctic Ocean and its dynamics (accumulation or release) is responsible for freshwater fluxes to the Atlantic Ocean. The heat content of the Arctic Ocean is potentially responsible for the sea ice melt and the Arctic atmosphere warm up. However, under the existing ocean state the majority of this heat is trapped in the Atlantic water layer and does not affect sea ice conditions. A change in the ocean vertical stratification or the ocean circulation could result in the release of this heat which could cause massive melting of the Arctic sea ice cover and, perhaps, even its disappearance.

From 2000 to 2005, the most complete observational data available to analyze changes in the freshwater and heat content of the Arctic Ocean are the intensive investigations conducted in the vicinity of the North Pole (North Pole Environmental Observatory, NPEO, Morison et al. (2002), http://psc.apl.washington.edu/northpole/) and the Western Arctic (Beaufort Gyre Observing System, BGOS, http://www.whoi.edu/beaufortgyre/index.html). Hydrographic data acquired in the North Pole region in the 1990s show a strong increase in upper ocean salinity relative to the Environmental Working Group Atlas of the Arctic Ocean (EWG, 1997) climatology (Figure 3, left panel), where water temperature and salinity from observations were averaged and gridded for the decades of 1950, 1960, 1970 and 1980. This increase was associated with a more cyclonic Arctic Ocean circulation in the 1990s. Under this condition, the fresh water from river runoff tended to circulate along ocean boundaries (see Figure 1, right panel, wide blue lines)

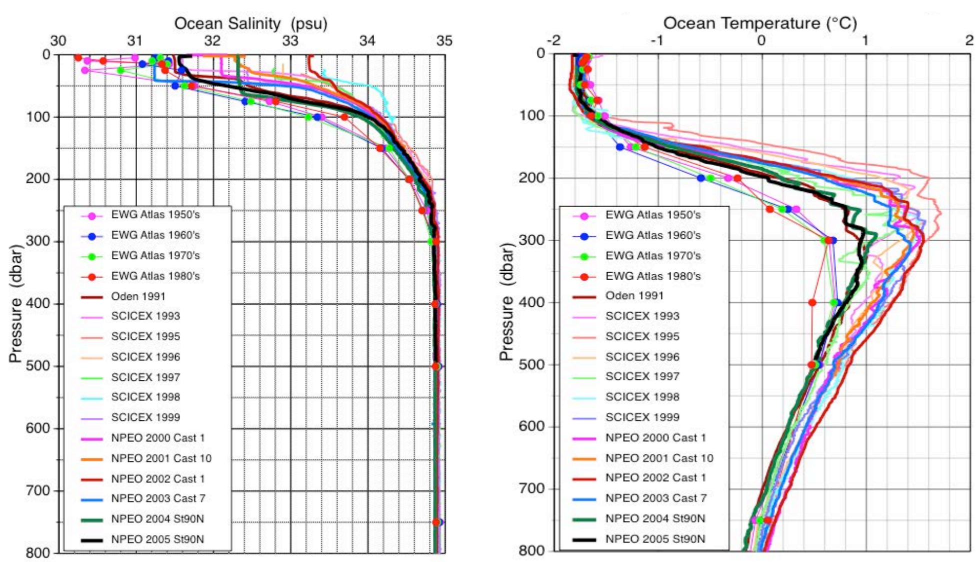

Figure 3. North Pole hydrography 1991-2005 (lines) compared with EWG climatology (lines with circles); left: salinity, right: temperature.

resulting in the decrease of salinity along coastlines and salinity increase in the central Arctic (North Pole). The NPEO-data also show a large increase in Atlantic Water temperature at depth relative to the EWG climatology (Figure 3m, right panel). This was also consistent with the cyclonic circulation regime conditions in the 1990s when more Atlantic water penetrated to the Arctic Ocean and, correspondingly, there was an increase in Atlantic water temperature. Hydrographic measurements made by the NPEO show that the conditions since 2000 have relaxed toward the pre-1990 climatology, but some changes still at least partially persist.

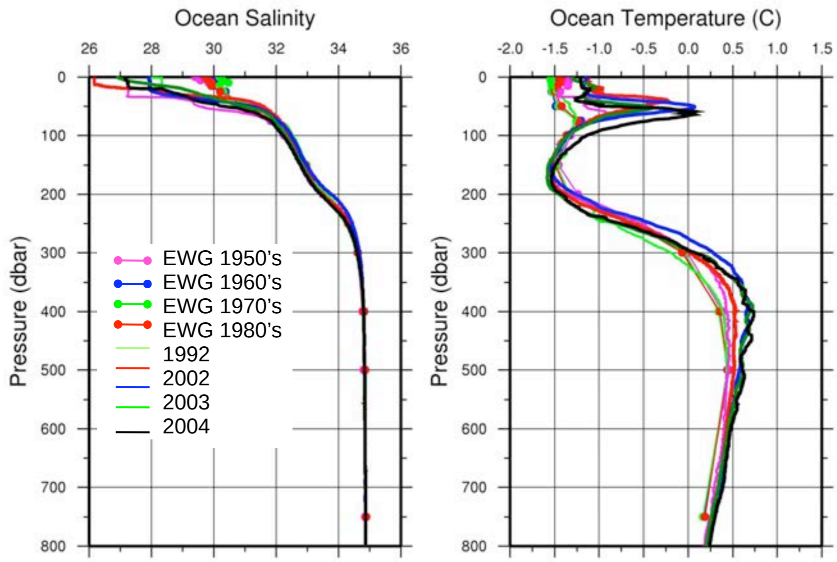

Figure 4. The Beaufort Gyre hydrography 1991-2005 (lines) compared with EWG climatology (lines with circles) for the vicinity of 75N and 150W; left: salinity, right: temperature.

The Beaufort Gyre (the major freshwater reservoir in the Arctic Ocean) hydrography has also changed dramatically relative to the 1990s (Figure 4). The results of several hydrographic surveys in this region in the 1990s compared to the EWG data indicate that, in opposition to the salinity increase at the North Pole, the salinity of the upper layer in the Beaufort Gyre was significantly reduced in the 1990s (Figure 4, left panel). This is a consequence of both sea ice melt during Arctic warming in the 1990s and the addition of fresh water from Siberian rivers. The shift in the pattern of fresh water transport is consistent with the presence of cyclonic winds, which redirect the ocean surface flow of fresh water from the Russian and Siberian coasts along the Siberian Seas to the Beaufort Sea. Under anticyclonic winds, this fresh water flows towards the Fram Strait (compare left and right circulation patterns in Figure 1, wide blue arrows). In the 2000s relative to 1990s, the salinity in the Beaufort Gyre was increased but was still approximately 1 unit less than the EWG climatology. There was also a very small salinity decrease in the 50-300 meter layer of the ocean but this change was within the range of interannual variability. Interestingly, the total freshwater content in the Beaufort Gyre in the 2000s has not changed dramatically relative to climatology but there has been a significant change in the freshwater distribution (Figure 5, panels 3 and 4). The center of the freshwater maximum has shifted toward Canada and significantly intensified relative to climatology.

In the 1990s, the water temperature in the Beaufort Gyre increased significantly relative to EWG data (Figure 4, right panel). As discussed in section 2.1, the most pronounced warming (up to 1°C) was observed in the Pacific water layer (50-100m), but the maximum heat accumulation was observed in the Atlantic waters between 200 and 800 meter layer. These waters, propagating cyclonically from the Fram Strait (Figure 1, red arrows), reached the Beaufort Sea in the late 1990s – much later than when they reached the North Pole. The combination of warming water temperatures and a change in the circulation pattern resulted in a significant increase of the heat content in the Beaufort Gyre in the 2000s relative to the EWG climatology and observations made in the beginning of the 1990s (Figure 5, panels 1 and 2).

Sea Level

Figure 6 shows sea level time series from several coastal stations in the Siberian Seas. There is a positive sea level trend along the arctic coastlines. From 1954-1989 the rate of sea level rise was estimated as 0.185 cm/year (Proshutinsky et al., 2004). Adding 1990-2004 data increases the estimated rate to 0.191 cm/year. Sea level time series correlates relatively well

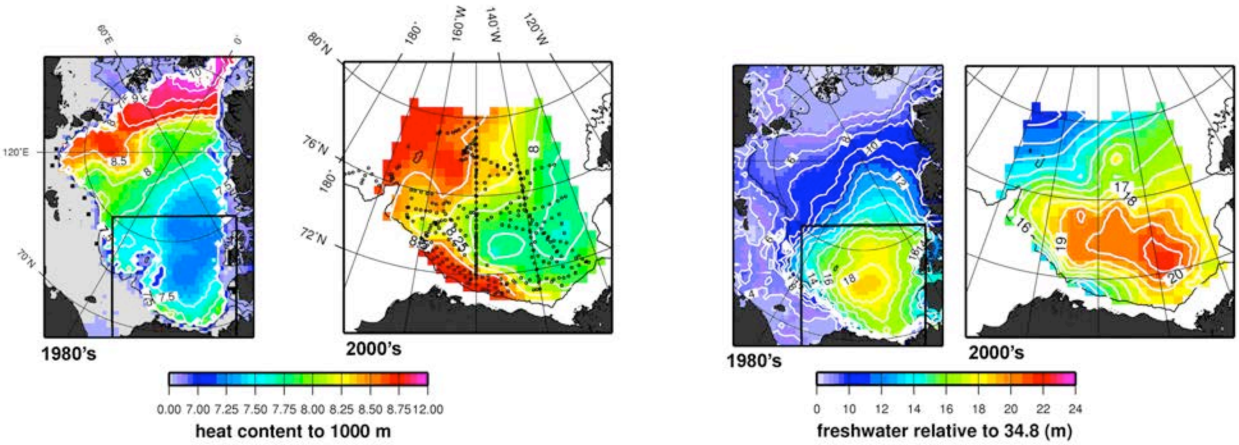

Figure 5. Summer heat (10^9 J/m^2, left) and freshwater (m, right) content. Panels 1 and 3 show heat and freshwater content in the Arctic Ocean based on 1980s climatology (EWG, 1998). Panels 2 and 4 show heat and freshwater content in the Beaufort Gyre in 2000-2005 based on hydrographic surveys (black dots depict locations of hydrographic stations). For reference, this region is outlined in black in panels 1 and 3. The heat content is calculated relative to the water temperature freezing point in the upper 1000m ocean layer. The freshwater content is calculated relative to reference salinity of 34.8.

with the AO index (correlation coefficient is 0.83). Consistent with the influences of AO-driven processes, sea level dropped significantly after 1990 and increased after the circulation regime changed from cyclonic to anticyclonic in 1997. In contrast, from 2000 to 2004 the sea level rise rate has increased in spite of a steady decrease of the AO index. At this point, because of the large interannual variability, it is difficult to evaluate the significance of this change.

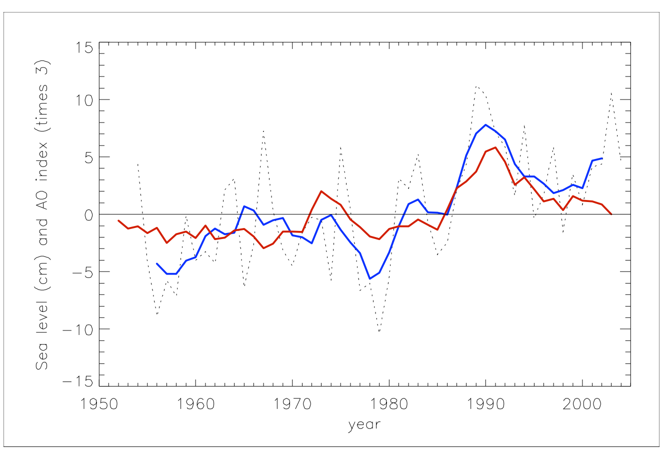

Figure 6. Annual mean relative sea level from 9 tide gauge stations in the Siberian Seas (dotted line). The blue line is the 5-year running mean sea level. The red line is the 5-year running mean AO index.

Sea Ice Cover - Extent and Thickness

During 2005 every month, except May, showed record minima sea ice extent in the Northern Hemisphere for the period 1979-2005. The extent of the sea ice cover is typically at or near its maximum in March and its minimum in September. The ice extent in March 2005 was 14.8 million km^2. In September 2005 the ice extent was 5.6 million km^2. In comparison, the mean ice extent for March and September, for the period 1979-2005, was 15.7 million km^2 and 6.9 million km^2, respectively (Figure 7). It is notable that in March 2005 the ice extent fell within the mean contour at almost every location. In September 2005, the retreat of the ice cover was particularly pronounced along the Eurasian and North American coastlines.

To put the 2005 minimum and maximum ice extent into context, the time series of the variability of ice extent in March and September for the period 1979-2005 are presented in Figure 8. In both cases, a negative trend is apparent, with a rate of 2% per decade for March and 7% per decade for September. The summers of 2002-2005 have marked an unprecedented series of extreme ice extent minima (Stroeve et al., 2005).

The state of the sea ice cover is intrinsically linked to the state of the ocean and atmosphere. This is confirmed by the observation that during this same period (1978-2005), the annual surface temperatures over land areas north of 60° N have generally been rising and

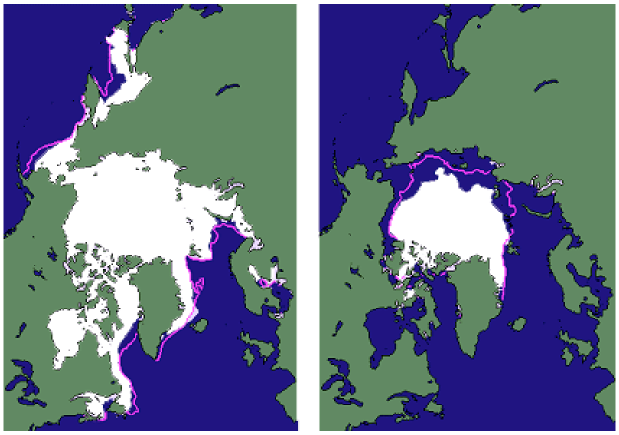

Figure 7. Sea ice extent in March and September 2005, when the ice cover was at or near its maximum and minimum extent, respectively. The magenta line indicates the median maximum and minimum extent of the ice cover, for the period 1979-2000. In both cases, the ice extent reached a record minimum in 2005, for the period 1979-2005. (Courtesy of National Snow and Ice Data Center, NSIDC)

have been above the mean value for the 20th century since the early 1990s (Figure 9).

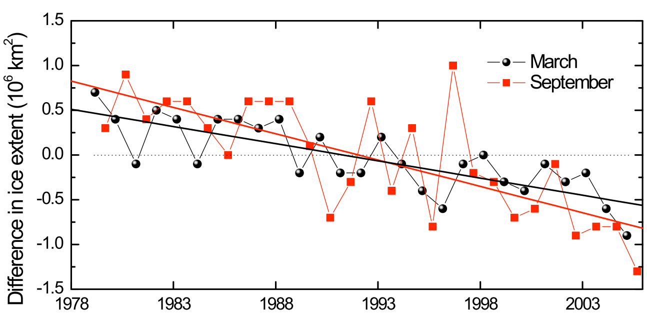

Figure 8. Time series of the difference in ice extent in March (maximum) and September (minimum) from the mean values for the time period 1979-2005. Based on a least squares linear regression, the rate of decrease in March and September was 2% per decade and 7% per decade, respectively.

Ice thickness is intrinsically more difficult to monitor, compared to ice extent. With satellite-based techniques (Laxon et al., 2003; Kwok et al., 2004) only recently introduced, observations have been spatially and temporally limited. Data from submarine-based observations, indicate that at the end of the melt season the permanent ice cover (ice located towards the center of the Arctic basin that survives is present all year round; see Figure 7, right panel) thinned by an average of 1.3 m between

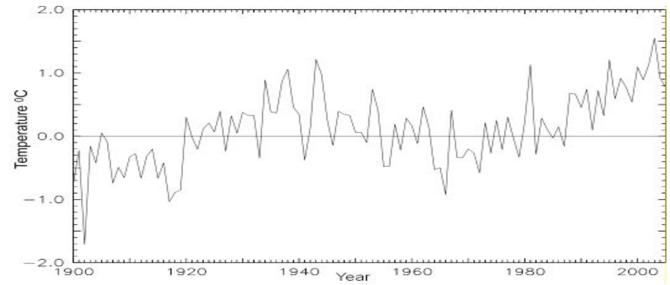

Figure 9. Arctic-wide and annual averaged surface air temperature anomalies (60° – 90° N) over land for the 20th century based on the CRU TEM2V monthly data set (courtesy of J. Overland).

the period 1956-1978 and the 1990s, from 3.1 m to 1.8 m (Rothrock et al., 1999). On the other hand, measurements of the seasonal ice cover (ice around the periphery of the Arctic basin that melts during the summer) do not indicate any statistically significant change in thickness in recent decades (Melling et al., 2005; Haas, 2004; Polyakov et al., 2003).

The trends in the extent and thickness of the cover are consistent with observations of a significant loss of older, thicker ice out of the Arctic via the Fram Strait (e.g. Rigor and Wallace, 2004; Pfirman et al., 2004; Yu et al., 2004) in the late 1980s and early 1990s (Figure 10). This event coincides with the strong, positive AO period which extended from 1989-1995 (see Figure 2). When the AO is positive, atmospheric and oceanic conditions favor a thinner ice cover. A relatively younger, thinner ice cover, like the one left behind from this event, is intrinsically more susceptible to atmospheric or oceanic warming. It is of great interest to observe whether the sea ice cover will continue its decline or rebound under the recent more neutral AO conditions.

Sea Ice Surface Conditions

Data from 1982-2004, derived from Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder extended (APP-x) products (updated from Wang and Key, 2005a,b), indicate an overall negative trend for summer (June-August) mean albedo of –0.4%/year (Figure 11a). The trend increases slightly to –0.5%/year for the period from April through September (Figure 11b), suggesting a possible increase in the duration of the melt season. In both cases, the surface albedo is relatively low from 2001 to 2004 and is consistent with observations of an earlier, more spatially extensive onset of melt and decreases in ice concentration (Belchansky et al., 2004; Stroeve et al., 2005).

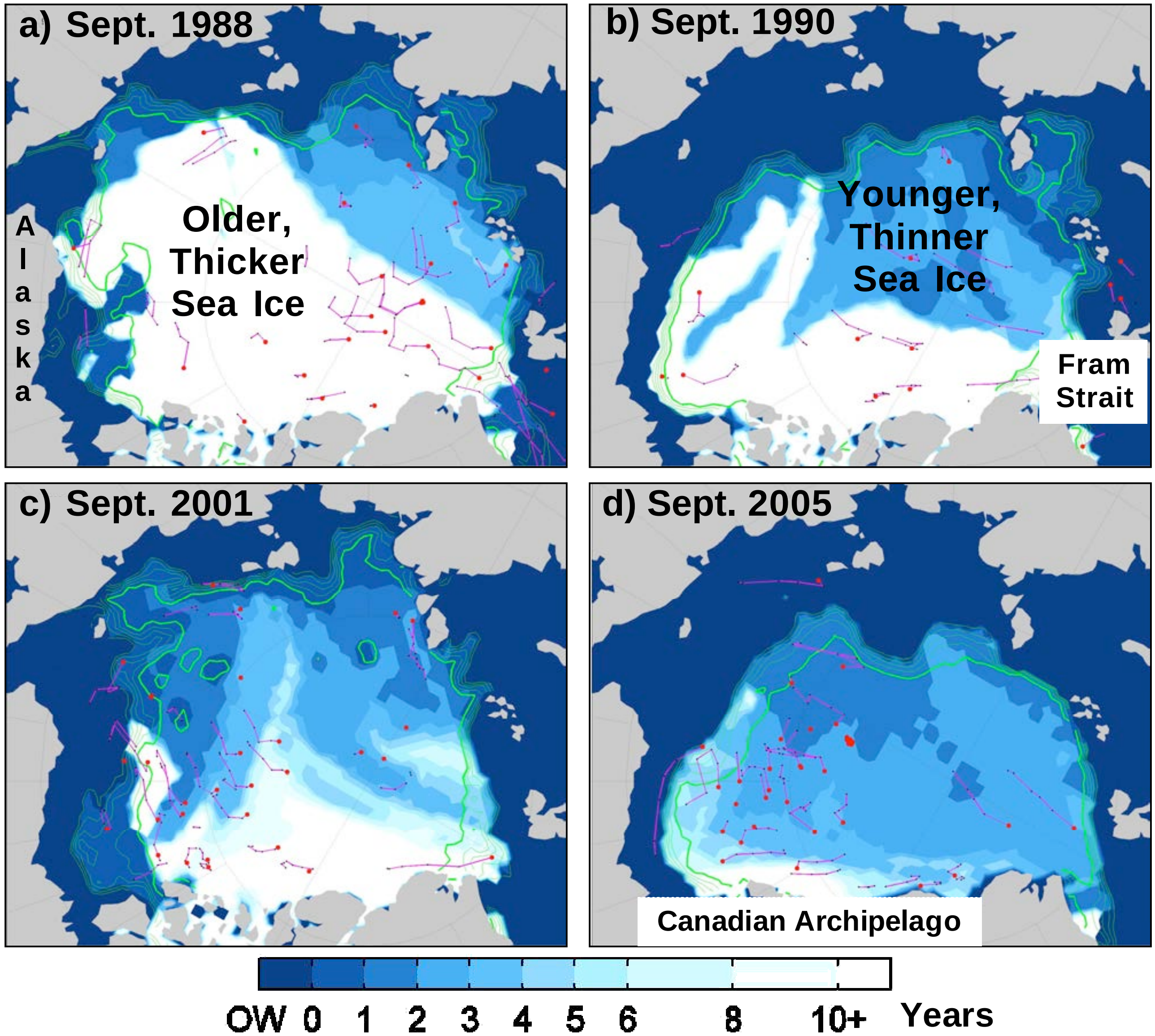

Figure 10. Change in the age of ice on the Arctic Ocean, compared for September and based on results from a simulation using drifting buoy data and satellite-derived ice concentration data (Rigor and Wallace, 2004). Open water (OW) is shown in dark blue and the oldest ice is shown in white. The darker green line marks 90% ice concentration and the lighter green lines mark ice concentrations of 80, 70, 60 and 50%. This sequence shows (a) most of the Arctic Ocean was covered by older, thicker sea ice in Sept. 1988; (b) coincident with a transition to high AO conditions in 1989 (see Fig. 2) most of the older, thicker sea ice was rapidly flushed out of Arctic Ocean through Fram Strait, so that by 1990 only 30% of the Arctic Ocean was covered by older, thicker sea ice; (c) persistence of the relative distribution between older thicker and younger, thinner sea ice during the 1990's, in spite of a shift back towards a more neutral AO condition in the mid-1990's; and d) extension of this work through 2005, suggesting a continued decrease in the average ice age over the Arctic Ocean, with older, thicker ice now limited to the area north of the Canadian Archipelago.

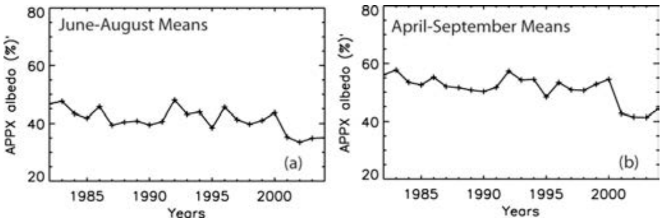

Figure 11. Time series of APP-x surface albedo for areas between 60° – 90° N and with ice concentrations of 15-100%. (a) Means averaged over June-August. (b) Means averaged over April-September.

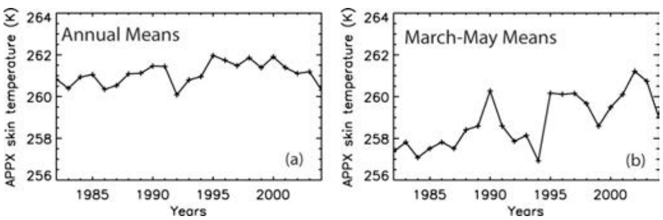

Figure 12. Time series of APP-x skin temperatures for areas between 60° – 90° N and with ice concentrations of 15-100%. (a) Means averaged over 12 months. (b) Means averaged over March-May.

The time series of APP-x annual mean skin temperatures (Figure 12a) over the same period shows less consistent change over time, with a general increase in annual mean temperatures through the early 1990's and a decrease from 1995 onward. When the time series is limited to spring (March-May) temperatures the 23-year linear trend is positive (0.14K/year), with greater interannual variability (Figure 12b), indicative of the seasonal dependence of warming trends.

Large regional variability, typical of arctic conditions, is observed in albedo, skin temperature and ice concentration (Cavalieri et al., 1997). From 1996-2004, the largest decreases in surface albedo correspond to a reduction in ice extent in the Beaufort and Chukchi seas, while lower albedos over the central ice pack appear consistent with the lower total ice concentrations over this same period. It remains to be determined how much of the albedo change is due to the presence of more open water vs. more extensive ice-surface melt and ponding. In either case, the changes represent significant modifications of the ice pack.

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The Global Ocean Carbon Cycle: Inventories, Sources and Sinks

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Background

The global utilization of fossil fuels is rapidly changing the trace gas composition of the Earth's atmosphere. These "greenhouse gases" play a critical role in controlling the Earth's climate because they increase the infrared opacity of the atmosphere, causing the planetary surface to warm. Carbon dioxide (CO_2) is the major anthropogenic greenhouse gas, contributing about 60% to the total change in radiative forcing due to human perturbations. As of the early 2000s, the release of CO_2 to the atmosphere from burning fossil fuels and cement manufacturing had grown to more than 7 Pg C per year (1Pg = 10^{15}g = 1 billion metric tons) (Marland et al., 2005). Of this amount, approximately 3 Pg C of this so-called "anthropogenic CO_2" accumulates in the atmosphere with distributions that are well documented through a global measurement network. The remaining 4 Pg C is sequestered by the terrestrial biosphere and global ocean. Where and how these two major sink regions (ocean and terrestrial biosphere) vary in their uptake of CO_2 from year to year is the subject of much scientific research (Prentice, 2001). Understanding this partitioning is critical because the ocean is believed to be a long-term sink for anthropogenic CO_2 while the terrestrial sink is more labile.

Several approaches have been used to estimate the ocean uptake of anthropogenic CO_2 for the decade of the 1990s (Table 1). There is a general consensus that the average oceanic sink for the 1980s and 1990s was about 1.9 ± 0.7 Pg C yr^{-1} (Figure 1; Sabine et al., 2004a). Most of these estimates, however, can not be used, a priori, to predict what the future ocean uptake will be or how feedbacks between the ocean carbon system and climate may alter the controls on sea-air CO_2 fluxes. Future policy decisions regarding possible

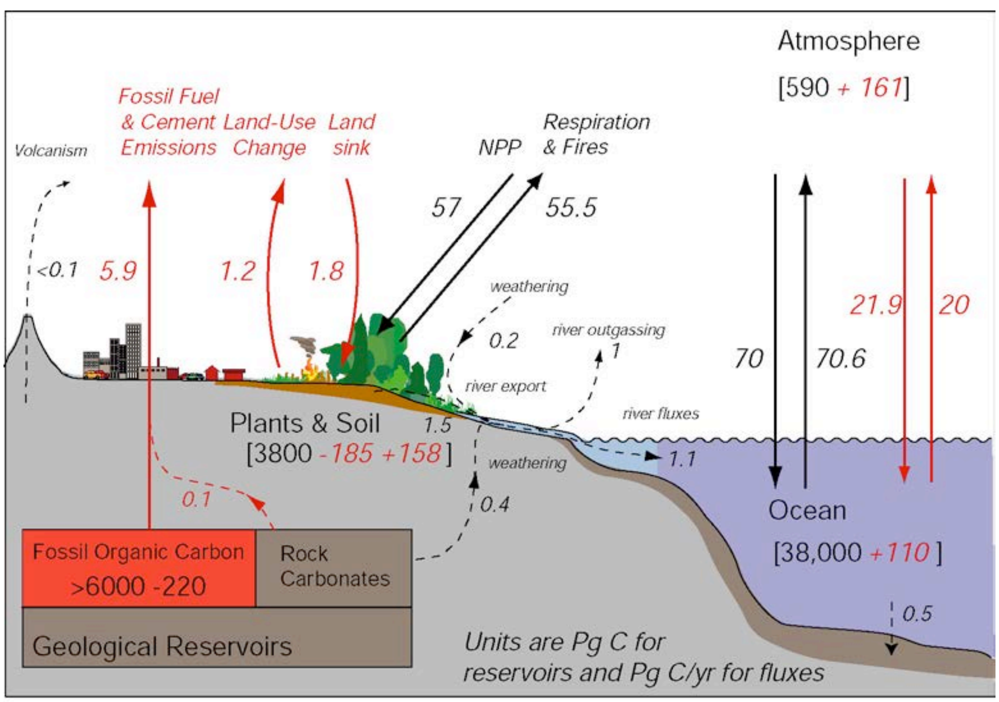

Figure 1. Schematic of global carbon cycle during the 1980s and 1990s. Black arrows represent natural fluxes and red arrows are anthropogenic fluxes (adapted from Sabine et al., 2004a).

Table 1. *Estimates of Oceanic Anthropogenic CO_2 Uptake in Pg C/yr.*

Method	Carbon Uptake (Pg C/yr)	Reference
Measurements of sea-air pCO_2 Difference	2.1 ± 0.5	Takahashi et al. (2002)
Inversion of atmospheric CO_2 observations	1.8 ± 1.0	Gurney et al. (2002)
Inversions based on ocean transport models and observed DIC	2.0 ± 0.4	Gloor et al. (2003)
Model simulations evaluated with CFC's and pre-bomb radiocarbon	2.2 ± 0.4	Matsumoto et al. (2004)
OCMIP-2 Model simulations	2.4 ± 0.3	Orr (2004)
Based on measured atmospheric O_2 and CO_2 inventories corrected for ocean warming and stratification	2.2 ± 0.5	Keeling et al. (2005)
GCM Model of Ocean Carbon	1.93	Wetzel *et al.* (2005)
CFC ages	2.0 ± 0.4	McNeil *et al.* (2003)

Fluxes are normalized to 1990-1999 (except Keeling & Manning which is for 1993-2004) and corrected for pre-industrial degassing flux of ~0.6 Pg C/yr.

greenhouse gas emission controls need to be based on predictive models of CO_2 sources and sinks and these models need to be adequately validated against sustained ocean carbon observing system measurements. Moreover, tracking the increases in ocean carbon content, and the associated ocean acidification, will contribute to an improved understanding of the effects of elevated CO_2 on ocean biota (Feely et al., 2004a; Orr et al., 2005).

Two basic approaches are being used to document changes in the ocean carbon system: 1) repeated trans-basin hydrographic sections (surveys of ocean properties in the water column along a cruise track) provide information on decadal scale changes in ocean inventories and transport within the ocean interior; and 2) high frequency (in space and time) observations of surface ocean and atmospheric CO_2 concentrations that can be used to estimate sea-air exchanges on seasonal to inter-annual time-scales. These two approaches provide information on ocean carbon changes over a complimentary range of time and space scales. The latest findings from the ocean carbon program are presented here. These findings are placed in context with a growing body of evidence documenting the carbon cycle changes in the ocean.

Ocean Inventories

In the 1990s, researchers from several countries worked together through two international programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), to conduct an extensive survey of the chemical and physical properties of the global ocean (Feely et al., 2001; Wallace, 2001). An analysis of more than 70,000 carbon measurements from this survey, found that the ocean accumulated approximately 118 Pg C between 1800 and 1994 (Sabine et al., 2004b). This accumulation accounts for 48% of the CO_2 released from burning fossil fuels over this same time period. Because the ocean mixes much more slowly than the atmosphere, more than half of this carbon can still be found in the upper 400 meters (Figure 2). The average penetration depth for CO_2 generated from human activity is about 1000 meters, roughly one quarter of the average global ocean depth. Most of the ocean volume, therefore, has not been exposed to the higher atmospheric CO_2 concentrations of the industrial era so we would anticipate that the ocean would continue to take up CO_2 for at least the next thousand years.

Because there were no ocean carbon measurements prior to the industrial revolution, the anthropogenic CO_2 component of the total dissolved inorganic carbon (DIC) concentration had to be estimated using a back calculation technique based on our understanding of the physical and biological contributions to the measured DIC. As a consequence, assumptions about steady state circulation and biology over these time scales had to be made. By repeating a subset of the cruises run in the 1990s, many of the assumptions required for the back calculation technique can be avoided and the changes in ocean carbon along a cruise track run at two different times can be directly evaluated.

The U.S. CLIVAR/CO_2 Repeat Hydrography Program started in 2003 with three cruises in the North Atlantic (Figure 3). Analysis of these repeated lines has indicated that several biogeochemical parameters are changing with time (Feely et al., 2005a). For example, changes of -10 to +30 μmol kg^{-1} of DIC have been observed in the upper 1000 m of the water column between the 1993 and 2003 occupations of A16N along 25°W in the North Atlantic (Figure 4a). Although the magnitude of the changes is expected, the patchiness of the changes was not anticipated. More surprisingly is the fact that there have been comparable changes in the Apparent Oxygen Utilization (AOU, a measure of the decomposition of organic matter in the ocean) of the waters indicating significant changes in the organic matter cycling over the last decade (Figure 4b). The complicated patterns of these changes clearly show that carbon is being influenced by more than simple secular changes in anthropogenic tracers. In some cases changes in circulation and organic matter decomposition may be masking the anthropogenic changes and in other cases these changes may enhance the apparent ocean carbon uptake.

Another intriguing preliminary finding from a comparison of recent cruises in the North Pacific and North Atlantic is an indication that anthropogenic carbon inventories may be increasing in the Pacific at about twice the rate of the Atlantic over the last 10 years (Feely et al., 2005a). This is in contrast to the long-term anthropogenic CO_2 inventory that shows larger column inventories in the North Atlantic, thus highlighting the variability in oceanic

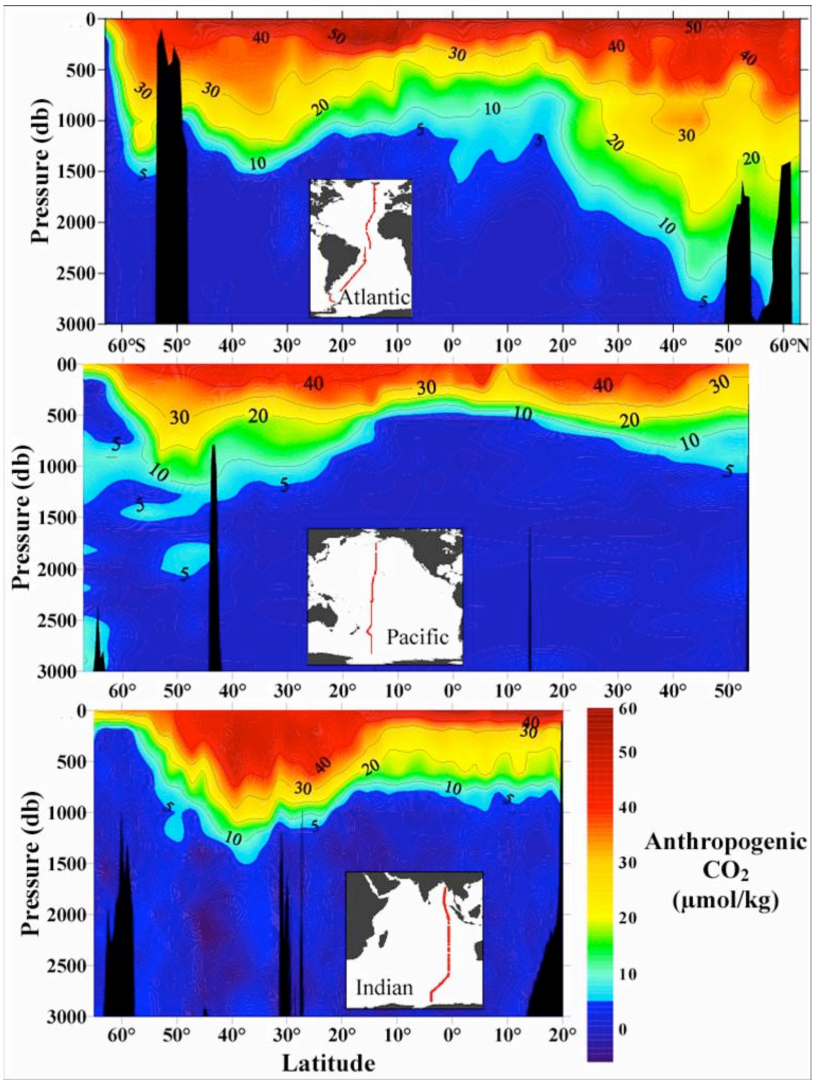

Figure 2. Example sections of anthropogenic CO_2 that has accumulated in the Atlantic, Pacific, and Indian oceans between 1800 and 1994 (modified from Sabine et al., 2004b).

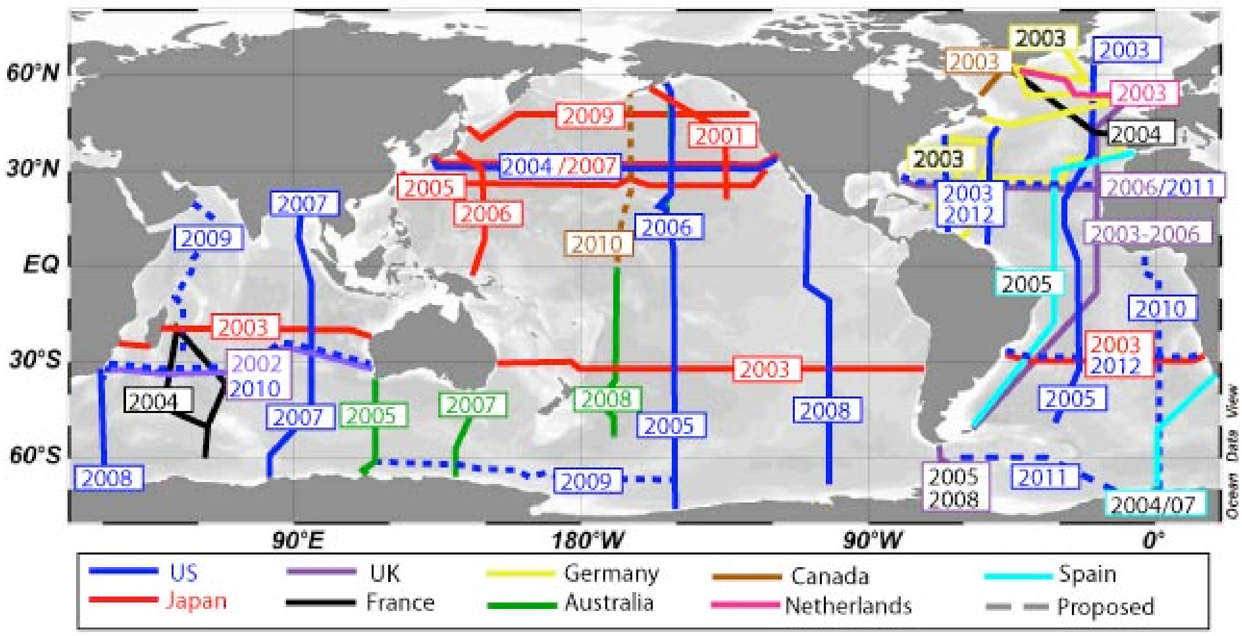

Figure 3. Map indicating recently completed and planned international repeat hydrography cruises. The U.S. CLIVAR/CO_2 Repeat Hydrography Program (indicated in blue) started in 2003 with three cruises in the North Atlantic.

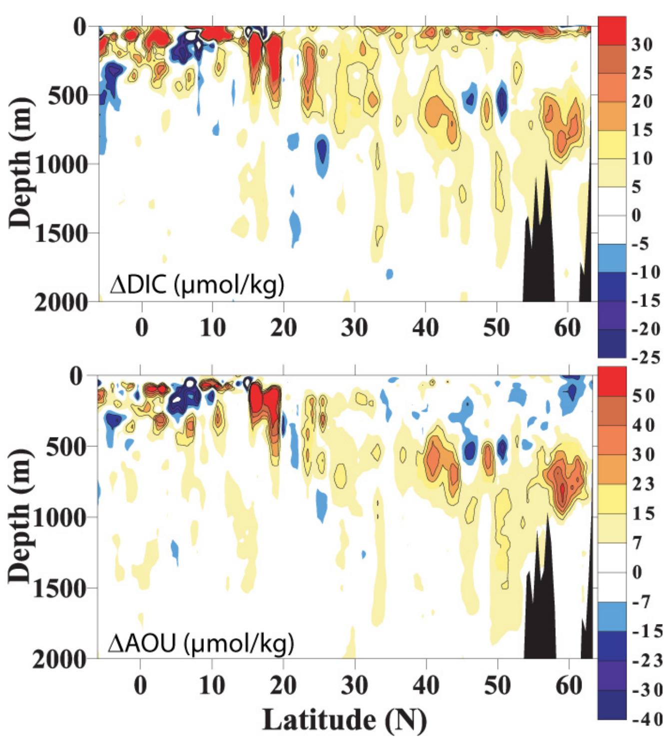

Figure 4. Changes in DIC (a) and AOU (b) between the 2003 and the 1993 occupations of A16N. Positive values represent an increase in concentrations between 1993 and 2003 (modified from Feely et al., 2005a).

sinks with time, and underscoring the challenge of predicting future oceanic uptake of atmospheric CO_2. The explanation for these recent findings may lie in understanding the effects of climate modes like the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO) on the decadal scale circulation. These results also point to the need for improved techniques for isolating the anthropogenic and natural components of the observed variability.

Ocean-Atmosphere CO_2 Fluxes

The temporal and spatial variability of the partial pressure of CO_2 (i.e. the contribution of CO_2 pressure to total gas pressure, pCO_2) in the surface ocean is large compared to the atmospheric pCO_2 variability. Atmospheric pCO_2 is well resolved by weekly flask sampling at ~50 stations around the world (Tans and Conway, 2005). Because of the greater variability, surface ocean pCO_2 distributions are only known in a climatological sense. Inferring a global CO_2 uptake rate is challenging because, the average pCO_2 of the atmosphere need only be ~7µatm higher than the global ocean pCO_2 to account for an ocean uptake of ~2 Pg of carbon each year. Taro Takahashi of Lamont-Doherty Earth Observatory and his collaborators have amassed adatabase of more

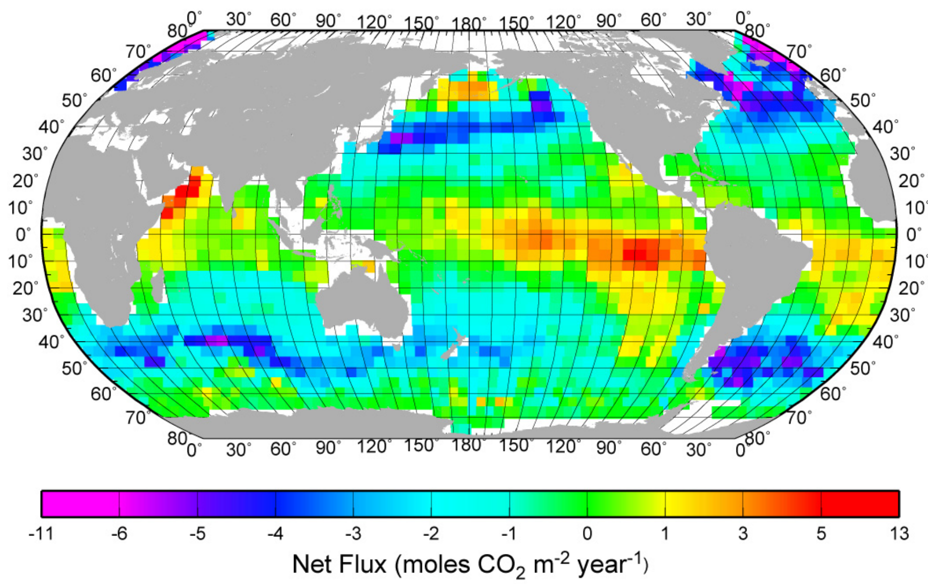

Figure 5. Annual sea-air fluxes for a nominal year of 1995. Positive values indicate a flux of CO_2 out of the ocean (Takahashi, 2002).

than 1.7 million surface ocean pCO_2 measurements, spanning more than 30 years, and derived a pCO_2 climatology for the global ocean (Takahashi et al., 2002). These data have been used to determine global and regional sea-air CO_2 fluxes with an average annual global open-ocean uptake of 1.5 ± 0.4 Pg C/yr for a nominal year of 1995 (Takahashi et al., 2002; revised by T. Takahashi, New York, 2005, personal communication). This flux estimate represents the total net flux in 1995. This is significant because prior to human intervention the oceans were a net source of CO_2 to the atmosphere of approximately 0.6 Pg C yr^{-1} (Sabine et al., 2004a). The total anthropogenic flux is the difference between the 1995 net sea-air flux and the estimated pre-industrial net sea-air flux (i.e. -1.5 – 0.6 = -2.1 Pg C/yr; see Table 1).

Figure 5 shows the global distribution of total net sea-air CO_2 fluxes. The yellow-orange-red colors indicate oceanic areas where there is a net source of CO_2 to the atmosphere, and the blue-purple colors indicate regions where there is a net sink of CO_2. The Equatorial Pacific is a strong source of CO_2 to the atmosphere throughout the year as a result of upwelling, which brings deep, high CO_2 waters to the surface in the central and eastern regions. This upwelling, and thus the CO_2 flux to the atmosphere, is heavily modulated by the El-Niño Southern Oscillation (ENSO) cycle (Feely et al., 2002, 2004b; Takahashi et al., 2003). During strong El-Niño years the equatorial Pacific CO_2 source can drop to zero as the upwelling is suppressed. During La Niña the upwelling, and thus the CO_2 source to the atmosphere, is enhanced**.** CO_2 outgassing fluxes are also observed in the tropical Atlantic and Indian oceans.

The CO_2 flux in the high-latitude ocean is governed primarily by deep convection in winter and biological uptake during the spring and summer months (i.e. outgassing in the winter and uptake in the spring/summer), whereas in the temperate and subtropical regions, the flux is governed primarily by water temperature (i.e., spring/summer warming causes outgassing and fall/winter cooling causes uptake). Outside of the equatorial belt and coastal upwelling regions, the ΔpCO_2 (seawater pCO_2 - atmospheric pCO_2, which drives the air sea exchange) is highest during winter in subpolar and polar waters, whereas it is highest during summer in the temperate regions. Thus, the seasonal variation of ΔpCO_2 and, consequently, the shift between net uptake and release of CO_2 in subpolar and polar regions is about 6 months out of phase with that in the temperate regions (Takahashi et al., 2002).

Although the Takahashi pCO_2 climatology has greatly improved our understanding of the sea-air flux patterns, it does not address the temporal variability in these patterns or the variability in the global net uptake. Substantial inter-annual variability in the Equatorial Pacific CO_2 flux (± 0.4 Pg C/yr peak-to-peak amplitude) has been well documented through sustained shipboard and moored time series measurements (e.g. Feely et al., 1995; Chavez et al., 1999; Feely et al., 2005b), but a paucity of measurements have limited similar assessments in other regions of the global ocean.

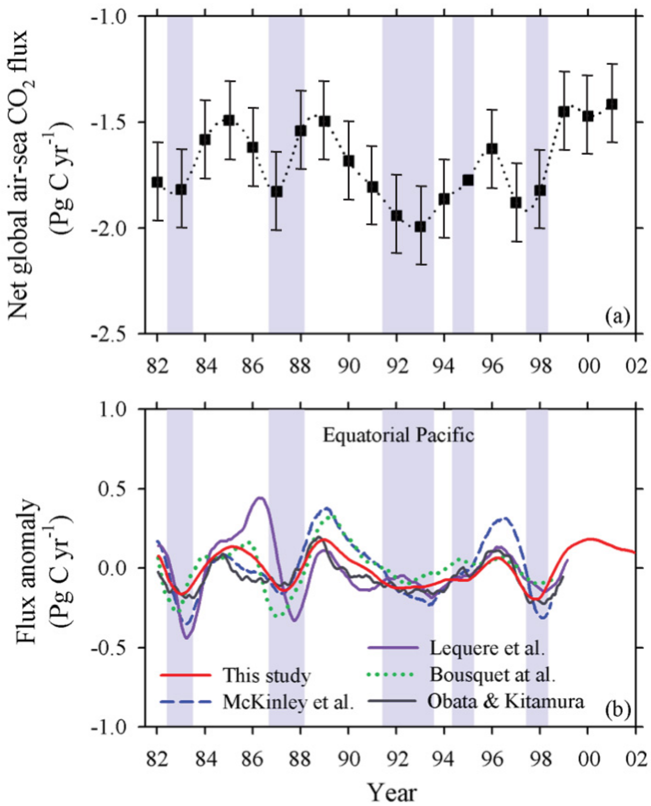

Figure 6. (a) Net global sea-air CO_2 fluxes in Pg C yr^{-1} from 1982 through 2001. The dotted line is a spline fit and error bars indicate estimated uncertainty in seasonal pCO_{2sw}/SST relationships only. Negative values correspond to net oceanic CO_2 uptake. Shaded bars indicate El Niño events (when SST anomaly is greater than 0.4°C in the Niño 3.4 region). (b) Comparisons of modeled CO_2 flux anomalies for the Equatorial Pacific (10°N−10°S, 80°W−135°E). For the period over which four independent estimates are available (1982−1997), modeled interannual variabilities obtained from Le Quéré et al. (2003), McKinley et al. (2004), Bousquet et al. (2000), Obata and Kitamura (2003), and the present study (Park et al., 2005) are ±0.18, ±0.18, ±0.14, ±0.13, and ±0.12 Pg C yr^{-1}, respectively (modified from Park et al., 2005).

.Recently, Park et al. (2005) used regional algorithms relating pCO_2 to satellite derived sea surface temperature anomalies to estimate CO_2 variability globally. They found the average inter-annual deviation of the global ocean CO_2 flux from the Takahashi climatology to be ±0.18 Pg C yr^{-1} for the period from 1982 to 2001. However, there are large uncertainties in this approach. The estimated uncertainty from the seawater pCO_2/SST relationships alone is as large as the estimated global inter-annual variability (Figure 6a).

In an effort to improve these regional algorithms, the international CO_2 community is developing a surface CO_2 observational network using volunteer observing ships, moorings, and drifting floats. These measurements together with modeling efforts can be used to better understand the controls on sea-air CO_2 fluxes. For example, approximately 70% of the global CO_2 flux variability is currently attributed to flux anomalies in the Equatorial Pacific (Figure 6b). The regional algorithm approach estimates a smaller inter-annual variability than most ocean model studies in this region. Our growing observational data base will allow us to make improved algorithms for the Equatorial Pacific (e.g. Feely et al., 2004b). Similar efforts are going on in subtropical regions where temperature exerts a dominant control on sea surface pCO_2 levels (e.g. Olsen et al., 2004, Wanninkhof et al, 2005).

In the high-latitude oceans the algorithms will require additional input parameters to account for the effects of deep convection and biological uptake on surface pCO_2. For example, the inclusion of mixed layer depth, obtained from the ARGO profiling floats, in the algorithms for these regions looks promising (Lueger et al., 2005). An expansion of the global observational network is needed in all parts of the global ocean to evaluate the uncertainties in the regional algorithm assessment of global inter-annual variability and to develop improved algorithms relating pCO_2 to satellite observations. With the proper observational program, the documentation of inter-annual CO_2 flux variability in the global ocean can be achieved.

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CHAPTER 3

THE STATE OF THE OBSERVING SYSTEM

Project Summaries

This chapter is derived from FY 2005 progress reports submitted to the Office of Climate Observation by scientists who are funded to deploy, maintain, and analyze the output of the global ocean observing system for climate. A request for annual reports was issued in early September, 2005. The material below, which is based on those reports, describes components of the global ocean observing system for climate, and summarizes the accomplishments of the program in FY 2005. Full text of the original reports may be found on the companion CD.

The chapter begins with a report describing the Climate Observation Program managed by the NOAA Office of Climate Observation, which is the primary sponsor of most of the projects presented below. The projects are listed in a table, that follows, that includes their accompanying web sites. The reports that follow are organized in accordance with the observing system networks described in the program plan that introduces this report, with additional sections reporting on ocean analyses and a variety of additional topics supported by the program.

PROGRAM OVERVIEW
FY 2005

The Sustained Ocean Observing System for Climate System Management

Mike Johnson
NOAA/Office of Climate Observation, Silver Spring, MD

Introduction

The Office of Climate Observation (OCO) resides within the Climate Program Office and manages the ocean sub-capability of the Climate Observations and Analysis Program. NOAA's Climate Goal, via the OCO, provides the backbone of the Global Component of the U.S. Integrated Ocean Observing System (IOOS). IOOS is the U.S. contribution to the international Global Ocean Observing System (GOOS), which is the ocean baseline of the Global Earth Observation System of Systems (GEOSS).

Figure 1. The Networks that make up the Sustained Ocean Observing System for Climate are (from lower left to upper right): Dedicated Ships, Ships of Opportunity, Ocean Reference Stations, Tide Gauge Stations, Arctic Observing Systems, Tropical Moored Buoys, Surface Drifting Buoys, Argo Profiling Floats, and Continuous Satellite Missions for sea surface temperature, sea surface height, surface vector winds, ocean color, and sea ice. Not illustrated are the Data & Assimilation Subsystems and Product Delivery.

It is the job of OCO to advance the multi-year *Program Plan for Building a Sustained Ocean Observing System for Climate.* The intended outcome is a sustained global system of complementary *in situ*, satellite, data, and modeling subsystems adequate to accurately document the state of the ocean and force climate models. The observing system is being put in place to meet climate requirements but it also supports weather prediction, global and coastal ocean prediction, marine hazard warning systems (e.g., tsunami warning), transportation, marine environment and ecosystem monitoring, and naval applications. Many non-climate users also depend on the baseline composite system that is nominally referred to as the sustained ocean observing system for climate.

Responsible Institutions

The "Networks" are managed by 19 distributed centers of expertise at the NOAA laboratories, centers, joint institutes, universities and business partners. The "System" is centrally managed at the Office of Climate Observation, a project office within the NOAA Climate Program Office (CPO). Specifically, OCO's tasks are to:

- Monitor the status of the globally distributed networks; report system statistics and metrics routinely and on demand;
- Evaluate the effectiveness of the system; take action to implement improvements through directed funding;
- Advance the multi-year program plan; evolve the *in situ* networks through directed funding;
- Focus intra-agency, interagency, and international coordination;
- Organize external review and user feedback; and
- Produce annual reports on the state of the ocean and the adequacy of the observing system for climate.

The distributed centers of expertise that are implementing NOAA's contributions to the system are at AOML, PMEL, ETL, GFDL, JIMAR (University of Hawaii), JIMO (Scripps Institution of Oceanography), CICOR (Woods Hole Oceanographic Institution), JISAO (University of Washington), CIMAS (University of Miami), CICAR (Columbia University), NCDC, NODC, CO-OPS, AMC, PMC, NDBC, NCEP, FSU (Florida State

University), and Service Argos Inc. The contributions of these centers are summarized by the project managers in their individual reports.

Across NOAA there are 45 Federal employees, and 105 non-Federal employees working to implement the system. Within the OCO project office there are four Federal employees, and four non-Federal; one of the OCO Federal employees is detailed to the international GOOS Project Office at UNESCO in Paris.

Partnerships are central

A global observing system by definition crosses international and institutional boundaries, with potential for both benefits and responsibilities to be shared by many. In addition to the work specifically supported through the OCO program, NOS, NMFS, and NWS maintain observational infrastructure for ecosystems, transportation, marine services and coastal forecasting that do or have potential to contribute to climate observation. NOS sea level measurements in particular provide one of the best and longest climate records existent. NESDIS data centers are essential. NMAO ship operations are necessary for supporting ocean work. NESDIS and NPOESS continuous satellite missions are needed to provide the remote sensing that complements the *in situ* measurements. All of the OCO contributions to global observation are managed in cooperation internationally with the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). The National Science Foundation has initiated their Ocean Observatories Initiative, which will potentially provide significant infrastructure in support of ocean climate observation. The ongoing NSF-NOAA cooperative project for CLIVAR-ocean carbon surveys has proved to be an interagency-international-interdisciplinary success. The Office of Naval Research maintains a GODAE data server at Monterey that is critical to global data access. The UNOLS fleet provides ship support for ocean operations. NASA's development of remote sensing techniques is key. The ocean climate research being conducted by the CPO science programs, other NOAA programs, NASA, NSF, and the Navy provides the advancements in knowledge that are essential for continuous system improvement.

\Goal and Objectives

The goal of the OCO is to build and sustain a global climate observing system that will respond to the long term observational requirements of the operational forecast centers, international research programs, and major scientific assessments. The focus is on building the *in situ* ocean component. The program objectives are to:

- document long term trends in sea level change;
- document ocean carbon sources and sinks;
- document the ocean's storage and global transport of heat and fresh water; and
- document ocean-atmosphere exchange of heat and fresh water.

Requirement Drivers

The ocean climate observing system must have the capability to deliver continuous instrumental records and analyses accurately documenting:

- Sea level to identify changes resulting from climate variability;
- Ocean carbon content every ten years and the air-sea exchange seasonally;
- Sea surface temperature and surface currents to identify significant patterns of climate variability;
- Sea surface pressure and air-sea exchanges of heat, momentum, and fresh water to identity changes in forcing function driving ocean conditions and atmospheric conditions;
- Ocean heat and fresh water content and transports to: 1) identify changes in the global water cycle; 2) identify changed in thermohaline circulation and monitor for indications of possible abrupt climate change; and 3) identify where anomalies enter the ocean, how they move and are transformed, and where they re-emerge to interact with the atmosphere; and
- Sea ice thickness and concentrations.

Present ocean observations are not adequate to deliver these products with confidence. The fundamental deficiency is lack of global coverage by the *in situ* networks. Present international efforts constitute only about 55% of what is needed in the ice-free oceans and 11% in the Arctic. The *Second Report on the Adequacy of the Global Observing System for Climate in Support of the UNFCCC* concludes that "the ocean networks lack global coverage and commitment to sustained operations…Without urgent action to address these findings, the Parties will lack the information necessary to effectively plan for and manage their response to climate change."

In response to the Second Adequacy Report, international GCOS produce the *Implementation Plan for the Global Observing System for Climate in support of the UNFCCC* (GCOS-92). GCOS-92 was published in October 2004. It has been endorsed by the UNFCCC; and was endorsed by the Earth Observation Summit III in Brussels, in February 2005. In particular:

1. The UNFCCC, Decision CP.10, "Encourages Parties to strengthen their efforts to address the priorities identified in the [GCOS] implementation plan, and to implement the priority elements …"
2. The *Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan Reference Document* 2-year targets include: "Support implementation of actions called for in the GCOS Implementation Plan."

OCO's *Program Plan for Building a Sustained Ocean Observing System for Climate* is in complete accord with GCOS-92 and provides the framework for NOAA contributions to the international effort. In particular 21 of the specific actions listed in the GCOS-92 ocean chapter (pages 56-84) are being acted upon by the OCO program in cooperation with the implementation panels of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), the International Ocean Carbon Coordination Project (IOCCP), and the Climate Variability and Predictability (CLIVAR) Program. These specific GCOS-92 actions now provide an excellent roadmap to guide observing system work over the next five years. GCOS-92 is accessible via link from the OCO web site: www.oco.noaa.gov -- click on "Reports & Products." All of the work supported by OCO is directed toward implementation of this international plan and the projects are being implemented in accordance with the GCOS Ten Climate Monitoring Principles. The OCO supported projects contributed 53% of the total international effort in 2005.

FY 2005 Accomplishments

Incremental advancements were accomplished across all of the networks. The international global ocean climate observing system overall advanced from 48% complete in FY 2004 to 55% complete in FY 2005. Breaking the 50% mark was celebrated at OCO's third Annual System Review, 25-27 April 2005 in Silver Spring, with the system being 51% complete at that time. The Annual System Review brought together 108 project managers, data users, advisors, and program managers both from NOAA and from other partner institutions to discuss system-wide issues and engage in program strategic planning. Additionally, a meeting of the JCOMM Observations Coordination Group (OCG) was held in conjunction with the NOAA Annual System Review, bringing international expertise and advice to the OCO program.

International coordination was solidified with both the OCO and the JCOMM OCG accepting the ocean domain of GCOS-92 as the roadmap for system implementation. The goals and objectives of OCO and JCOMM are now essentially identical. OCO's *Program Plan for Building a Sustained Ocean Observing System for Climate* was used as basis for development of JCOMM's *Initial Work Plan for Building a Sustained Ocean Climate Observing System in Support of the Global Earth Observation System of Systems*. This work plan was submitted to GEOSS by JCOMM as support for three GEOSS Target Work Packets:

- Target Work Packet 27: Support GSN and GUAN networks, Global Atmosphere Watch (GAW) observatories, initial Global Ocean Observing System (GOOS), river discharge, lake levels, soil moisture, permafrost, snow cover and glacier observing networks, which are recommended in the GCOS Implementation Plan.
- Target Work Packet 28: Support implementation of actions called for in the GCOS Implementation Plan and the relevant IGOS-P Theme Reports.
- Target Work Packet 34: Support JCOMM to coordinate the implementation of and prepare regulatory and guidance information for an operational *in situ* ocean observing system.

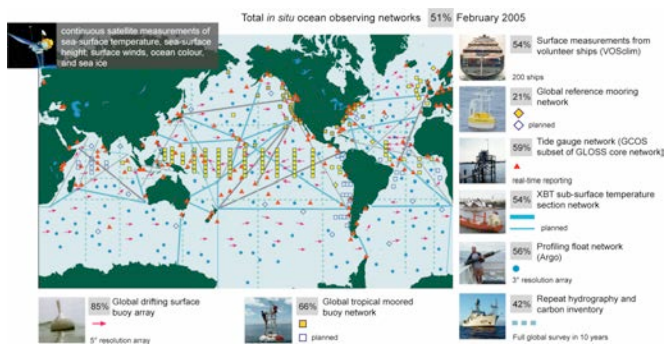

Figure 2: A schematic of the initial composite ocean observing system, including the current status against the targets of JCOMM and the GCOS Implementation Plan (GCOS-92), maintained by the international GOOS Project Office. The statistics were calculated by OCO as a national contribution to the international effort. This report was issued in February as the system passed the 50% mark.

During the Annual System Review, the progress of the NDBC/PMEL TAO Transition project was reviewed in the context of the draft NOAA Policy on Transition of

Research to Application. The Climate Observing System Council (COSC) recommended that the Transition Board assume oversight of the TAO transition project in accordance with the new policy. This recommendation was accepted by the Board.

A significant new programmatic direction was initiated in 2005 with OCO launching an Ocean Analysis initiative. The initiative is intended to advance the routine delivery of ocean analysis products, and is in response to the recommendations from the first and second Annual System Reviews. These reviews both identified lack of ocean analysis as a major gap that needed to be filled by NOAA. Routine ocean analyses are essential not only to document the state of the changing ocean but also as basis for evaluating the effectiveness of the system. In 2005 OCO established a partnership with NCEP to help support the routine delivery of data sets and outputs from NCEP's Global Ocean Data Assimilation System (GODAS) for community-wide use. The files are now being made available by EMC while CPC is developing visualization products and a web site for access to the products and the GODAS files. In addition, a team of expert scientists was assembled under support from this initiative to develop data based analyses for evaluating the system and products, and to recommend improvements to both. Initial evaluations by this team will form the core of the agenda for the fourth Annual System Review in 2006.

A historic milestone was achieved on 18 September 2005 with the deployment of Global Drifter 1250 near Halifax. With this deployment, the global drifting buoy array reached its design goal of 1250 data buoys in sustained service and became the first component of the Global Ocean Observing System to be fully implemented. A special ceremony, organized and cosponsored by OCO, was held to commemorate this achievement in conjunction with the second session of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). It took 10 years to reach this milestone from the time that the international community set out to implement a global observing system with the *Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System*, which was published by the Ocean Observing System Development Panel in 1995. Eighty-seven representatives from 16 counties participated in the ceremonial deployment of Global Drifter 1250.

The year 2005 was a banner year in many other respects. The observing system made major strides forward, surpassing the planning target of 53% and achieving 55% complete by September. The jump of 7% from 48% complete in 2004 to 55% complete in 2005 was the largest advance ever recorded in a single year. The reports of the Project Managers outline specific advancements of the individual networks. Highlights include:

- *Documenting long-term trends in sea level change*: Following the tragic Indian Ocean tsunami of 24 December 2004, tide gauge stations were upgraded for real-time reporting to contribute to the international tsunami warning system as well as to the climate reference network; upgrading to real-time reporting became the top priority for the OCO program rather than geocentric location; and the University of Hawaii Sea Level Center led the international community in rapid response and in the advancement the multi-use platform concept. The transition from NASA to NOAA of responsibility for the long-term support of the Harvest Platform altimeter calibration station was completed.
- *Documenting the ocean-atmosphere exchange of heat and fresh water*: Global Drifter 1250 was deployed as highlighted above. U.S. expansion of the Tropical Moored Buoy network into the Indian Ocean began; four Indian Ocean sites were established in November 2004 by PMEL in cooperation with Indian partners. In the Atlantic Ocean, PIRATA was extended in cooperation with Brazil and France with three new moored buoy sites being established in the South West Expansion.
- *Documenting the ocean's storage and global transport of heat and fresh water*: The Argo array continued its rapid progress toward global coverage, passing the 2/3 mark of 2000 floats in service. The transition of the Indo-Pacific high-resolution XBT lines from NSF to NOAA long-term support was completed; NOAA thus became the sole agency of the United States supporting this sustained component of the international system. In cooperation with the Brazilian navy, a new high-resolution XBT line was established to monitor upper ocean transport in the western Atlantic.

- *Documenting ocean carbon sources and sinks*: The global inventory of ocean carbon is needed at least once every 10 years; systematic surveying of the ocean was initiated in partnership with NSF but the level of funding was only adequate for NOAA to complete its contribution to the global effort in at best 14 years; in FY 2005 NOAA augmented the project to bring the rate of survey up to the required 10-year cycle. Three new moored buoy sites were established for time series ocean carbon monitoring, two in the Pacific and one in the Atlantic.

- *Data management*: A new tariff rate for data processing within the international Joint Tariff Agreement, which supports the Argos satellite data transmission/distribution system, established OCO as a preferential bulk user; OCO is the largest single government user of the Argos system in the world; the new agreement transferred all primary and supplemental costs to central management at OCO and saved an estimated 45 % in data processing costs system wide.

Integrated Ocean Observing System Global Component Budget Allocation ($K)				
Network	FY 02	FY 03	FY 04	FY 05
IOOS-Tide Gauge Stations	670	710	970	1196
IOOS-Drifting Buoys	1699	2077	2769	3130
IOOS-Tropical Moored Buoys	3175	3175	3625	4360
IOOS-Ships of Opportunity	1960	1903	2487	2907
IOOS-Argo Profiling Floats	271	275	273	249
IOOS-Ocean Reference Stations	1712	2082	2998	2995
IOOS-Ocean Carbon Networks	1478	2204	2875	3521
IOOS-International Arctic Ocean Observing System	337	337	337	397
IOOS-Dedicated Ship Time	0	626	523	92
IOOS-Data & Assimilation Subsystems	1286	1323	1487	1418
IOOS-Service Argos Data Processing	813	480	1525	1408
IOOS-Product Deliver, Analysis/Reanalysis	578	638	896	1982
IOOS-Institutional Infrastructure	626	653	1269	1356
IOOS Global Systems Total (OCO managed)	14605	16483	22034	25011
IOOS Argo Program (managed separately)	6978	9706	9811	9491
IOOS Arctic Program (managed separately)	1600	4322	3651	4928
OCO Funding Distribution				
NOAA				13944
External				9043
Service Argos				1408
Community Support (workshops, panels, JCOMM, CLIVAR, GOOS)				616
Total Global Systems, OCO managed				25011
OCO Income Budget Lines				
OAR Laboratories & Joint Institutes				5613
OAR Climate & Global Change Program				4886
OAR Climate Observations & Services Program				14156
Other				356
Total				25011

Table 1: System Funding Record

FY 2005 Projects, Authors, and Websites

Project	Authors	Web Site	Page
Tide Gauge Stations			
1. Global Sea Level Observations	Mark Merrifield	http://uhslc.soest.hawaii.edu	115
2. Operation of the National Water Level Observation Network	Stephen K. Gill, Chris Zervas	http://tidesandcurrents.noaa.gov http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml	119
Drifting Buoys			
1. The "Global Drifter Program" - Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure	Peter Niiler	http://www.aoml.noaa.gov/phod/soto/gsc/index.php	121
2. Surface Drifter Program	Silvia Garzoli, Bob Molinari, Rick Lumpkin	http://www.aoml.noaa.gov/phod/dac/ http://www.aoml.noaa.gov/phod/soto/gsc/index.php http://www.aoml.noaa.gov/phod/dac/dacdata.htm	124
3. Global Drifter Program - Fabrication of 22 Hurricane Thermistor Chain Drifters	Peter Niiler		128
Tropical Moored Buoys			
1. An Indian Ocean Moored Buoy Array for Climate	Michael J. McPhaden		130
2. Pilot Research Moored Array in the Tropical Atlantic (PIRATA)	Michael J. McPhaden	http://www.pmel.noaa.gov/pirata/	133
3. NOAA's PIRATA Northeast Extension	Robert L.Molinari, Rick Lumpkin, Claudia Schmid, Michael J. McPhaden		136
4. FY 2005 Tropical Atmosphere Ocean (TAO) Array	Landry Bernard	http://www.pmel.noaa.gov/tao/	137
Ocean Reference Stations			
1. Ocean Reference Stations	Robert A. Weller, Albert J. Plueddemann	WHOI website: http://www.whoi.edu UOP Group site: http://uop.whoi.edu Stratus Project site: http://uop.whoi.edu/projects/Stratus NTAS Project site: http://uop.whoi.edu/projects/NTAS WHOTS Project site: http://uop.whoi.edu/projects/WHOTS OceanSITES http://www.oceansites.org/OceanSITES	142

2. Western Boundary Time Series in the Atlantic Ocean	M. Baringer, C. Meinen, and S. Garzoli	http://www.aoml.noaa.gov/phod/wbcts/	150
3. Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)	Meghan F. Cronin, Christian Meinig, Christopher L. Sabine	http://www.pmel.noaa.gov/keo/	159
4. Weddell Sea Moorings	Arnold Gordon	http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml	163
5. High Resolution Climate Data From Research and Volunteer Observing Ships	C. W. Fairall	http://www.etl.noaa.gov/et6/air-sea/ http://www.etl.noaa.gov/programs/oceanobs/	164
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1. Global Sea Level Observations

Mark Merrifield
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PROJECT SUMMARY

This project supports the UHSLC (University of Hawaii Sea Level Center) activities to promote the development and continued operation of tide gauges for global sea level observations in support of climate research. In particular, the UHSLC is concerned with those stations that contribute to the Global Climate Observation System (GCOS). This effort is coordinated with the international community primarily through ties with the Intergovernmental Oceanographic Commission (IOC) Global Sea Level Observing System (GLOSS).

The UHSLC is an end-to-end provider of sea level information, taking part in data collection, processing, distribution, scientific analysis, and public outreach. To this end, the UHSLC plays a direct role in operating and maintaining over 40 international tide gauge stations, with 4 in the GCOS Category 1 list and 27 in the Category 2 list. The measurements are used for the evaluation of numerical models (e.g., those in operation at NCEP), joint analyses with satellite altimeter datasets, the calibration of altimeter data, the production of oceanographic products through the WMO/IOC JCOMM Sea Level Program in the Pacific (SLP-Pac) program, and research on interannual to decadal climate fluctuations. Also, in support of satellite altimeter calibration and validation and for absolute sea level rise monitoring, the UHSLC and the Pacific GPS Facility maintain co-located GPS systems at select tide gauge stations (GPS@TG).

Over the years the UHSLC has participated in various national and international programs including NORPAX, TOGA and WOCE, and currently is a designated CLIVAR data assembly center and an IOC GLOSS data archive center. Data collected by the UHSLC is managed to meet both the requirements of GLOSS and NCDC's ten climate monitoring principles. The UHSLC distributes in situ sea level directly from its dedicated web site, http://uhslc.soest.hawaii.edu, through an OPeNDAP server, PMEL's CDP, the NOPP sponsored NVODS project, and the NOSA geospatial and geospatial metadata databases being developed at NGDC. We also are providing in-situ sea level data to the GODAE program. The center also collaborates with NODC to maintain the Joint Archive for Sea Level (JASL), which is a quality assured database of hourly sea level from selected stations from around the world.

The primary UHSLC operations are administered under the Joint Institute for Marine and Atmospheric Research (JIMAR) co-operative agreement, and funded by the Office of Climate Observation. GPS@TG projects have been supported by OGP in the Atlantic Ocean, and by NASA for stations in the Pacific and Indian Oceans. We are working with other groups associated with the global observing system to provide syntheses of various datasets and to compile and distribute associated products.

FY 2005 PROGRESS

Tide Gauge Operations

The UHSLC plays a direct role in operating and maintaining over 40 international tide gauge stations, with 4 in the GCOS Category 1 list and 27 in the Category 2 list. During FY 2005, the UHSLC installed 4 new stations in the GCOS network (Colombo, Sri Lanka; Mar del Plata, Argentina; Salvador, Brazil; Ko Taphao Noi, Thailand). Station maintenance included on-site service trips to Hanimadoo, Male, Gan , Papeete, Easter, Yap, Palau, and Cape Verde where we also installed a new GPS. New stations were also installed at Port Louis and Rodrigues, Mauritius; Sibolga , Indonesia; and Ushuaia, Argentina. Stations that developed problems that our technicians were able to solve remotely included Socorro, Tern Island, Mombassa, Lamu, Seychelles, Sibolga, Palau, Yap, Saipan, Penhryn, Kanton, Diego Garcia, Colombo, Easter Island, Valparaiso, Chatham Island, Noumea, and the GPS sites at Male, Settlement Point, and Manzanillo . We are continuing to upgrade key network sites to radar sensors in place of the older float gauges, and an on-site data storage devices are being installed as a back-up system when satellite transmissions fail.

The 2004 Sumatra earthquake has led to an international drive to build the Indian Ocean Tsunami Warning

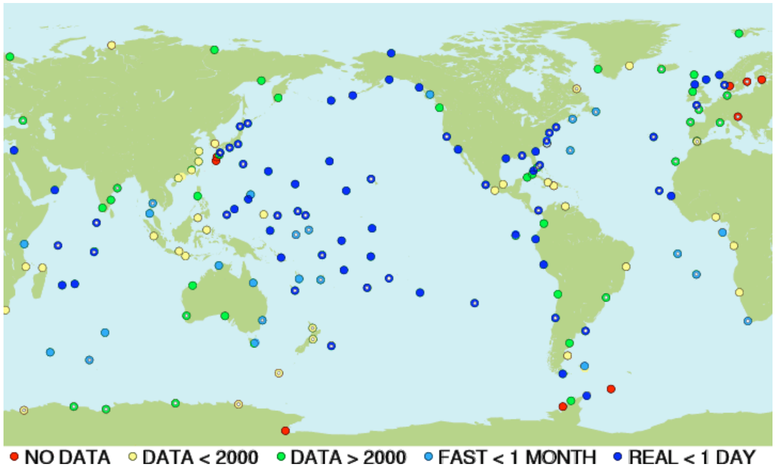

Figure 1. GCOS stations coded by data availability as of 10/12/05. There are 69 sites with hourly real-time data, 25 additional sites with hourly fast delivery data, 9 sites with hourly data later than 1999, 26 sites with hourly data before 1999, 61 sites with monthly data later than 1999, and 7 sites with monthly data before 1999. 69 sites have nearby DORIS or GPS (indicated on the map by a white dot).

System (IOTWS). Following the example in the Pacific, the IOTWS will rely on a network of coastal stations as well as Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys for detecting tsunami waves. As a starting point for the coastal station array, IOC GLOSS is promoting the upgrade of existing GLOSS tide gauge stations in the region to tsunami warning capability. The UHSLC maintains the majority of GLOSS stations in the Indian Ocean that were capable of measuring the December event in near-real time. In FY 2005, the UHSLC embarked on an ambitious program to configure GCOS/GLOSS stations as multiple-use platforms; robust enough to sample the full extent and fast response of a tsunami or storm surge, yet stable and reliable enough to provide information on longer-term sea level variations. Currently, in accordance with tsunami monitoring recommendations put forward by the IOC, data from 5 upgraded UHSLC stations in the Indian Ocean region are being transmitted via satellite to tsunami warning centers at 15-minute intervals. Plans for an additional 20 stations are under way. A reliance on multiple-use coastal stations, with a broad user base, maximizes the likelihood of continued maintenance and operation of the observing system for the benefit of generations to come. In addition, the network supports NOAA's ongoing efforts to understand environmental phenomena ranging from extreme events to climate change. We are also working with the Asia Disaster Preparedness Center (ADPC) in an effort to reestablish real time GCOS/GLOSS sites in the Southeast Asia region. The UHSLC is represented on both the IOTWS and the Pacific intersession working groups on sea level and will ensure that the proposed standards for the tsunami sea level stations are suitable for climate monitoring. The UHSLC accomplished all of its technical goals for the year, with the exception of a planned station at Minicoy Island, India, for which host country support has not been forthcoming.

The UHSLC continues as a partner providing technical support to the ODINAFRICA project, which will oversee the installment of 10-20 new tide gauges in Africa. The center is working with the Survey of India (SOI) on a plan to install satellite transmitting gauges at selected Indian GLOSS and GCOS sites, and to produce a quality assured database of hourly sea level from selected Indian stations. A MOU between NOAA and BAKOSURTANAL in Indonesia has been drafted for the purpose of upgrading the Indonesian tide gauge network. The UHSLC will help install up to 6 new gauges in the region, and contribute ongoing technical and scientific support for the operation of the network.

We have completed 7 GPS installations to date, and we are continuing to explore opportunities for further expansion in this area. We are negotiating with the Azores about a possible installation at Ponta Delgado. The center is also in discussions with the National Tidal Centre of Australia concerning their Indian Ocean and South Pacific gauges, and with agencies in Brazil.

Dataset Holdings

The Joint Archive for Sea Level (data latency: 1-2 years) is a collaborative arrangement between NODC, the World Data CenterA for Oceanography, and the UHSLC. The JASL is currently supported by NCDDC. The JASL produces a quality assured database of hourly sea level from stations around the world. In the past year, the UHSLC increased its JASL holdings to 10,461 stationyears, including 5874 stationyears at 209 GLOSS sites. Of the 101 GLOSS stations that are presently operating on islands, 97 are available through the JASL. The 2005 submission of the JASL data to the World Data Center-A for Oceanography included 103 series that contained measurements through the year 2004. We are also working with IPRC to ensure that the JASL delayed mode observations are available through the APDRC servers.

The UHSLC maintains a fast delivery database (data latency: 1 month) in support of various national and international programs (e.g., GODAE, CLIVAR, GLOSS, GCOS). To ensure active participation and coordination with the international community, the database has been designated by the IOC as a component of the GLOSS program. The fast delivery data are used extensively by the altimeter community for ongoing assessment and calibration of satellite altimeter datasets. In particular, fast delivery data are used for monitoring the latest JASON altimeter and for the tie between JASON, TOPEX/Poseidon, ERS, and GEOSAT satellites. The fast delivery sea level dataset now includes 166 stations, 130 of which are located at GLOSS sites, and 92 at GCOS sites.

We are working with the GODAE steering committee to ensure that tide gauge information in real-time is available through the UHSLC. Approximately 70 stations currently are available on this time frame with plans for ongoing expansion. Construction of the web site is ongoing, with recent development focused on netCDF formats via an OPeNDAP (formerly DODS) server.

As part of the JCOMM SLP-Pac, the UHSLC operates a Specialized Oceanographic Center that produces sea surface topography maps (monthly) and diagnostic time series (quarterly) for the Pacific Ocean. This activity is a continuation of one of the earliest examples of operational oceanography. The analysis includes comparisons of tide gauge and altimeter sea surface elevations that are available through the UHSLC web site.

The center produces CD-ROMs that mirror the UHSLC web site. These CDs are distributed with the JASL annual data report, shared with all data originators, and sent to other users upon request. Over 100 were distributed again last year.

Research Highlights

Research during FY05 focused on extreme events, interdecadal fluctuations, and sea level rise estimates. A description of the 2004 Indian Ocean tsunami as measured by tide gauges was also published.

A manuscript describing decadal oscillations in sea level in the eastern Pacific was published in the Journal of Physical Oceanography. We have described how the long sea level record collected at the Honolulu tide gauge is connected to Pacific North America (PNA) related fluctuations in winds and surface pressure. Connections with sea level fluctuations along the North American coast are also examined.

Extreme events and flooding at Tuvalu are associated with anomalously strong annual sea level high stands. The wind forcing forcing of this signal is still under review. We have tried to use simple wind-forced models and NCEP wind stress to explain the anomalies, however, the results have been inconclusive. We next will examine GCM outputs to see whether predictability is increased.

We documented the importance of anticyclonic eddies in establishing the highest sea level stand ever recorded on the island of Oahu, Hawaii. These eddy features travel significant distances across the eastern Pacific prior to impacting the Hawaiian Islands. The generation and dynamic behavior of these events are under investigation. A GRL paper describing the phenomenon was published during FY05.

A GRL manuscript describing land and ocean trends in the Hawaii region made use of continuous GPS and tide gauge observations to shed light on sea level rise issues. Differences in sea level rise rates recorded at Hilo and Honolulu have long been attributed to variable subsidence rates associated with volcanic activity. Continuous GPS measurements indicate that the rates are more similar between the islands. We find that recent sea level rate differences are due in part to steric variations associated with large-scale wind patterns.

Estimates of coastal sea level rise in the Southern California region are being made in conjunction with Ben Brooks at the Pacific GPS Facility. SAR images are used to estimate vertical ground motion along the entire coastal strip. Tide gauge and GPS information are then incorporated to give a full description of relative sea level variability along the coastline. We anticipate that the method will be applicable to many populated coastal areas. Once the Southern California case study is completed, we plan to extend the analysis to other major coastal cities along the west and east coasts of North America.

A preliminary estimate of land motion at the Maldives tide gauge station at Male is complete. We are evaluating how reference frame uncertainties affect that estimate. We hope to have a paper by next year analyzing the sea level rise problem in the Maldives based on the GPS measurements.

Appendix: Notes on the GCOS Sea Level Index

The GCOS tide gauge (TG) stations have been selected to estimate:

1. Global Sea Level (GSL) rise, and
2. Relative Sea Level (RSL) rise, particularly at heavily populated coastlines.

Over suitably long time scales, the primary difference between GSL and RSL rates is due to land motion.

Satellite altimeters (Alt), which have the capability of a truly global integration, are the preferred instrument platform for measuring GSL. Over the typical life span of coastal tide gauges (10-100 years), regional sea level fluctuations are likely to mask the local component of GSL rise in tide gauge records.

Tide gauges do play an important complementary role, however, in that the stability of the altimeter time series (particularly when multiple missions are involved) can be assessed by comparison with the tide gauge network. Gary Mitchum of the University of South Florida has led this analysis.

Tide gauges are the preferred method for assessing RSL. Altimeters play an important complementary role by providing an estimate of the local rate of change of the ocean. The link between the time rates of change (Δ) of the 2 measurements, within residual error ϵ, is then provided by a suitable land motion estimate

$$\Delta TG + \Delta Land = \Delta Alt + \epsilon$$

or

$$\Delta(TG - Alt + Land) = + \epsilon$$

The GCOS sea level index has been obtained by computing Δ(TG - Alt) at all stations with at least one year's worth of overlapping data. **We have not yet included estimates of Land motion**. The resulting trend differences are depicted in Figure 2.

A histogram of the trend differences (Figure 3) indicates that the mean difference is close to 1 cm/decade, and that the standard deviation is *. The scatter is presumably due to sampling errors (e.g., too short a record to determine statistically reliable trends), and/or the neglect of land motion.

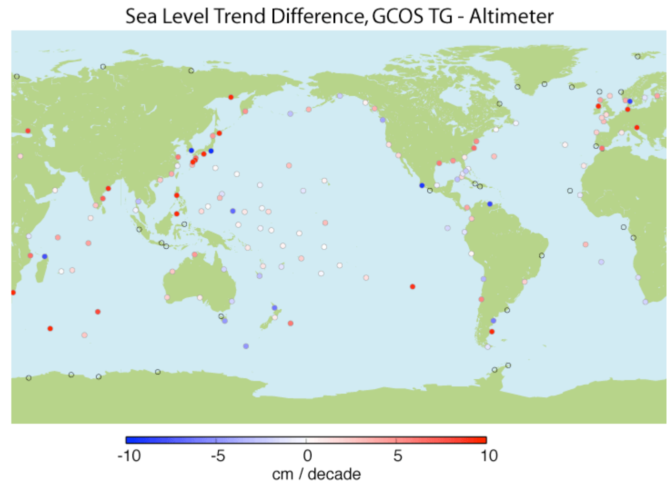

Figure 2. The linear trend of the sea level difference between GCOS tide gauges and Topex/POSEIDON and Jason-1 altimeter data. An open circle indicates that no GCOS data are available during the altimeter record.

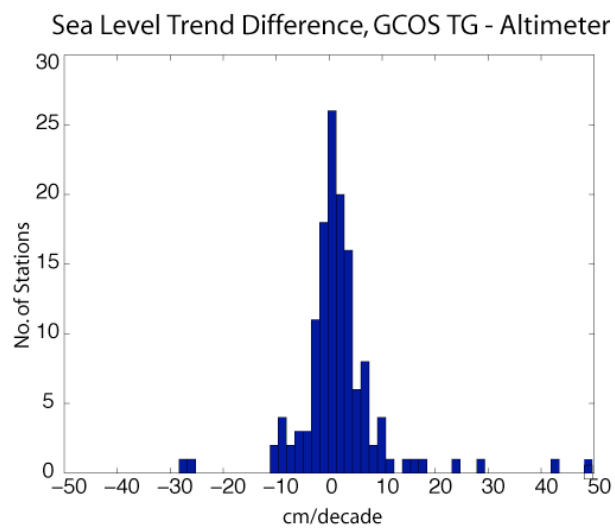

Figure 3. Histogram of the linear trend of the difference between TG and Alt.

Note that if we can include suitable Land motion estimates at the TG sites, then the <u>mean of the distribution</u> is related to the difference in GSL rates between the TG and Alt instrument platforms.

Our Sea Level Index is the <u>standard error</u> in estimating the mean,

SL Index = (standard deviation of ϵ)/ sqrt(N)

where N is the number of TG stations used in the analysis.

We want this Index to be as small as possible, or in other words, we want the error in determining the mean trend difference to be small. This is achieved by:

1. correcting the TG rates for land motion (e.g., with GPS rates)
2. obtaining long records in time to improve reliability of the trend differences
3. increasing N, the number of GCOS stations with useable data

As we steadily improve the GCOS network and reduce the SL Index, we will have the capability to:

1. provide an assessment of the statistical reliability of altimeter derived GSL trend (similar to Mitchum)
2. estimate RSL trends at the 190 GCOS stations around the world
3. specify land motion at the TG sites

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2. Operation of the National Water Level Observation Network

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PROJECT SUMMARY

This project implements sea level observations by the National Ocean Service Center for Operation Oceanographic Products and Services (CO-OPS) in support of the NOAA Climate Program Office. The NOAA National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) implements the following two tasks:

1. Upgrade the operation of selected National Water Level Observation Network Stations to ensure continuous operation and connection to geodetic reference frames

2. Operate and maintain water level measurement systems on Platform Harvest in support of calibration of the TOPEX/Poseidon and Jason 1 satellite altimeter missions.

An ancillary task, to develop and implement a routine annual sea level analysis reporting capability that meets the requirements of the Climate Observation Program, is described elsewhere in this report.

The NOAA National Water Level Program's (NWLP) National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network that's strives to meet NOAA's mission needs for tides and water levels. The NWLP is an end-to-end program that is planned, managed, and operated to provide products that meet user-driven needs. The program also consists of technology development, continuous quality control, data base management, and operational readiness and fully open web-site for data delivery. Sea level products are made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities.

Ocean Island Station Operations

There are several coastal and island NWLON stations critical to the Global Climate Observing System. The operation and maintenance of the ocean island stations of the National Water Level Observation Network (NWLON) has been increasingly more difficult over time due to the slow abandonment of the island facilities at which the stations reside. Finding routine flights and flights which are cost effective are becoming increasingly difficult, yet these stations require high standards of annual maintenance to ensure the integrity of their long term data sets. Annual maintenance is even more important, in light of the fact that corrective maintenance is logistically very difficult and expensive.

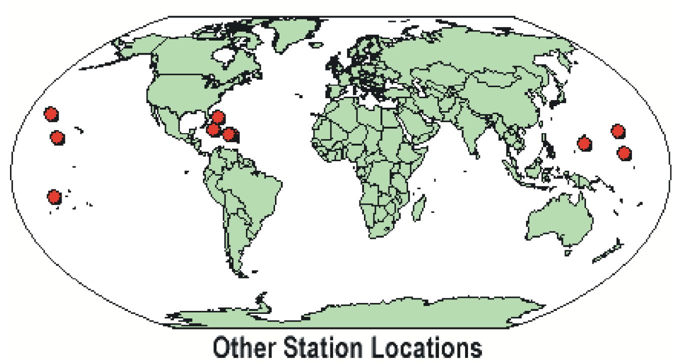

Figure 1. Ocean Island NWLON Station Map

Although operation of all of the stations is important, the Ocean Island stations are being given highest priority for upgrade to ensure their continuous operation (program funding and budget initiatives will be used for operation of the coastal stations). The upgrades include high accuracy acoustic or paroscientific pressure sensors and redundant Data Collection Platforms (DCP's) with equal capability to the existing primary systems. The station operations are also being enhanced with GPS connections to geodetic systems followed by installation of CORS (Continuously Operating Reference Station GPS) at selected sites. The following ocean island NWLON stations are receiving priority: Guam; Kwajalein; Pago Pago; Wake; Midway; Adak; Bermuda; San Juan, PR; Magueyes Island, PR; Charlotte Amalie, VI; St Croix, VI.

Satellite Altimeter Mission Support

Support for the TOPEX/Poseidon satellite altimeter mission began with installation of an acoustic system and a digibub system on Platform Harvest (Figure 2) in 1983, and continues with the operation of two digibub pressure systems collecting continuous water level data streams surveyed into the Platform and Satellite Orbit Reference frames.

CO-OPS special support has included a vertical survey on the Platform necessary to relate the water level sensor reference zeros (near the bottom catwalk) to the GPS reference zero (located up top at the helipad on the Platform. Continuous data are required to monitor effects of waves on the water level measurements and to ensure provision of data during the times of altimeter overflights every ten days. The original acoustic system was replaced by a digibub pressure system prior to the Jason-1 altimeter launch.

FY2005 PROGRESS

Ocean Island Station Operations

Maintenance of the ocean island NWLON stations continued using FY'05 CO-OPS resource levels. Using funding supplemented by one-time FY'05 Integrated Ocean Observing System (IOOS) funding, the upgrades of the stations a Midway and Guam were completed.

Satellite Altimeter Mission Support

Operation and maintenance of the Platform Harvest station continued the past year using Office of Climate Observation (OCO) funding. Coordination of activities continues with JPL. One of the pressure systems requires repair to bring it back online, however continuous data have been maintained. JPL is arranging for underwater maintenance of the bubbler pressure system orifices. JPL continues to provide reports on the status of the verification project at Platform Harvest.

1. The Global Drifter Program - Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure

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PROJECT SUMMARY

Rationale

The principal scientific questions of the role of the ocean in climate change are how well can we describe or model the ocean circulation today and how well can these descriptions or models predict the evolution of future climates. Drifters provide the near operational instrumental data sets for describing ocean surface circulation and SST evolution and these data are used for testing climate models and enhancing long-range weather prediction. Sensors that measure sea surface salinity, SSS, can now be added to drifters and SSS data are critical to determining the oceans' fresh water cycle and onset of deep-water renewals. Atmospheric pressure is assimilated into weather prediction models and is used by operational meteorological agencies to discern severe weather conditions over the oceans. Wind sensor and subsurface temperature chain data are used to improve prediction of tropical storm and hurricane intensities.

Objectives of the Global Drifter Program

The "Global Drifter Program" (*GDP*) is the principal international component of the JCOMM "*Global Surface Drifting Buoy Array*". It is a Scientific Project of the DBCP of WMO/IOC. It is a near-operational ocean-observing network of drifters that, through the ARGOS satellite system, returns data on ocean near-surface currents, SST and atmospheric pressure (and winds, subsurface T(z) and SSS) and provides a data processing system for scientific utilization of these data. In addition to *GDP*, drifters are deployed by operational oceanographic and meteorological agencies and individual scientific research projects, whose data are utilized by *GDP*. In turn, *GDP* data are made available to operational users and scientists at large. Wind-sensors, salinity sensors and thermistor chains are added to SVP drifters, presently on a limited basis for specific operational and research requirements. The international protocols for these data exchanges and sensor additions are worked out each year by DBCP.

The scientific objectives of the *GDP*, and its operational and research partners, are:

1) Provide to GTS an operational, near-real time data stream of SST, sea level pressure and surface velocity.

2) Observe the mixed layer velocity on a global basis with 0.5° resolution and, jointly with satellite altimeter data, produce new charts on the seasonal and interannual changing circulation of the world ocean at 0.5° resolution.

3) Develop and introduce into the drifter construction technological advances in sensors, electronics, power, methods of assembly and deployment packaging.

4) Provide enhanced research quality data sets of ocean circulation that include drifter data from individual research programs, historical data from instruments different from the Surface Velocity Program (SVP) Lagrangian Drifter and the corrected data sets for wind-produced slip of drifter velocity. To this end *GDP*:

- Provides to the coupled ocean-atmosphere climate modelers gridded, global data sets of SST, near surface circulation and dynamic topography for assimilation and the verification of the parametrized processes, such as wind-driven Ekman currents and spatial patterns of circulation (Figure 1).

- Provides the Lagrangian data sets for the computation of single particle diffusivity, dispersal of ocean pollutants, the enhancement of models of fisheries recruitment and improvement of air-sea rescue.

- Obtains high-resolution coverage of ocean variability and time mean circulation in support of ENSO prediction model verification in the tropical Oceans and supports short-term research projects that require enhanced upper ocean velocity observations.

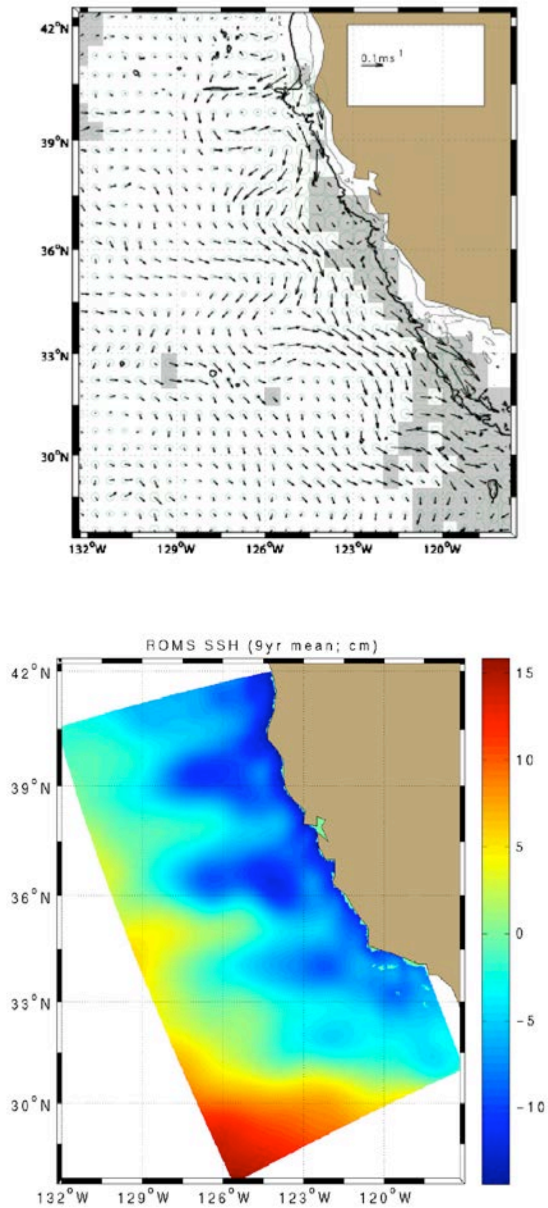

Figure 1. The drifter mean geostrophic velocity of the California Current (top panel) and mean sea level from ROMS model (bottom panel, courtesy of J. McWilliams). In both drifter data and model appear heretofore unknown four semi-permanent meanders.

Required Drifter Observations and Status of Global Array

GDP began in 1988 as a TOGA research program. WOCE made contributions in the period 1991-1993. Between 1992 and 2003, an array of 600 SVP drifters was maintained in the global ocean with contributions of resources from a variety of operational and individual research programs. Since October 2003 the array has consisted of over 900 drifters. Full implementation of the global array for SST observations will be completed by September 2005.

The 'required' global drifter array size by JCOMM is based on the need to maintain 1250 platforms that return instrumental observations of daily average SST (+/- 0.10C) over the global ocean at a 5º resolution, or the spatial scale of the error covariance function of operational NOAA satellite infrared SST sensors. Surface pressure sensors are also supported by regional meteorological agencies based on regional needs. The actual number of drifters in the array will be larger than 1250 because the required uniform spatial distribution will be difficult to maintain in the complex ocean surface circulation and many drifters go ashore in remote locations and continue to transmit. On July 25, 2005, 1209 of the 1250 'required' drifters are reporting to GTS and to the AOML Drifter Data Center (Figure 2). NOAA Climate Observations Program, together with cooperation of ONR, has funded

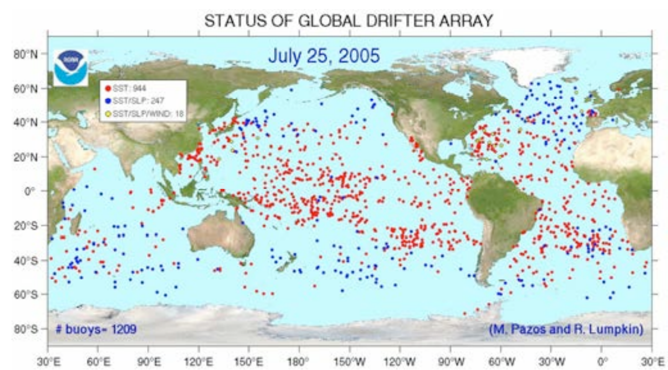

Figure 2. The Global Drifting Buoy Array on July 25, 2005.

sufficient numbers of SVP drifters (925) in FY'05, and with the expected contributions of drifters (200-300) from other sources, the array will be fully deployed by September 2005. In 2005 will begin more directed efforts to adjust the array spatial density with more uniform coverage. Present distribution covers about 60% of the surface of the ice-free ocean at 5º resolutions.

The requirements of the international science bodies, such as JCOMM, from the drifter array are to provide instrumental observations of SST and from met agencies to provide atmospheric pressure observations. Even though no internationally mandated operational requirement for surface velocity exists, nearly all research program contributions to the drifter array have been justified on the basis of upper ocean velocity observations. In the research community 99% of reviewed scientific research papers make principal use of drifter velocity observations: (viz. list of peer-reviewed research publications at: http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html). We anticipate that in the very near future, a surface velocity observation requirement will also be instituted.

Management

GDP reports every year on its activities relative to advances in technology in the DBCP Technical Session and in deployment plans and management in the DBCP Plenary Session. *GDP* is largely a NOAA funded program and is managed according to the "*Ten Climate Monitoring Principles*" established by JCOMM. In these tasks, the principal investigator assumes the responsibility for the coordination between the following entities:

- US manufacturers in private industry (*Technocean, Inc.* of Cape Coral, FL; *Clearwater, Inc.* of Watertown, MA; *Pacific Gyre, Inc.* of Carlsbad, CA) who build the SVP drifters according to closely monitored specifications. Internationally, a total of 6 private firms and 3 research laboratories build SVP drifters. Periodically, drifter construction manuals are upgraded and are posted on the DBCP website.

- Atlantic Oceanographic and Marine Laboratory (AOML) which carries out the deployments at sea, processes the data and archives these at MEDS, Canada, maintains the META file on the description of each drifter deployed, and the upgrades the *GDP* website.

- Joint Institute of Marine Observations at the Scripps Institution of Oceanography (JIMO) which supervises the US industry, acquires the NOAA funded drifters, upgrades the technology, develops sensors and enhanced data sets and maintains liaison with individual marine research programs that deploy SVP drifters.

FY2005 PROGRESS

In FY'04 NOAA Grants office funding of the *GDP* through JIMO, and the ancillary CORC, occurred in the last week of September 2004. This in essence is a report of what was accomplished with both the FY'04 and FY'05 funding during the calendar year September 2005-July 2005:

Summary of Drifter Acquisitions and Technology

905 drifters with SST sensors were built and most of these were delivered to AOML for deployment before June 2005. Because the FY'05 NOAA funding will not arrive at JIMO until late September 2005, in May 2005 JIMO acquired permission from the UCSD Chancellor for advance spending of $400K for purchase of an additional 220 SVP drifters. These were delivered to AOML for deployment by July 30, 2005.

1. A total of 550 SVP-Mini drifters were ordered from Clearwater Instruments, Inc and Technocean, Inc. These were delivered to AOML for deployment. Component parts for an additional 210 SVP-Mini drifters were ordered (jointly with ONR funds) from Clearwater Instruments, Inc and Pacific Gyre, Inc. These component parts were sent to Busan National University for assembly and are being deployed in to the western Pacific in support of CORC and ONR joint sponsored activities.
2. A total of 125 SVP-B drifters were ordered from Technocean, Inc. and Pacific Gyre, Inc. These were deployed under the direction of AOML in the North Pacific and the Southern Ocean.
3. A total of 20 Minimet wind-drifters were ordered from Pacific Gyre, Inc. At JIMO, 8 100-m long thermistor chains were built and attached to Minimet wind drifters. All 20 units were configured for air-deployment by the 53rd Air Force Reserve "Hurricane Hunter Squadron" into the Atlantic hurricane(s?) during the 2005 season. Dr. Rick Lumpkin and Dr. Peter Black at AOML are jointly directing their deployments into targeted hurricanes.
4. Components for a total of 20 SVP-Sea Surface Salinity (SSS) drifters were ordered from Seabird, Inc. and Pacific Gyre, Inc. These were assembled at SIO and 12 were deployed by MeteoFrance in April and May 2005 into the Bay of Biscay. Dr. Gilles Reverdin, at University of Paris, is successfully directing the recalibration via ships of opportunity; 8 were sent for deployment into the East China Sea to study the effects of the construction of the Great Yangtze River Dam.
5. Equal purchases of drifters each year are made from three US small manufacturers: with FY'05 funding the planned purchases, besides the 220 SVP-Mini drifters already purchased with the

UCSD Chancellor's advance from Technocean (90) and Pacific Gyre (130) are:

- 400 SVP-Mini drifters from Clearwater, Inc.
- 187 SVP-B drifters from Technocean, Inc.
- 113 SVP-B-Mini drifters from Pacific Gyre, Inc
- 20 Minimet wind drifters from Pacific Gyre, Inc.

In FY'05 JIMO will have purchased 940 drifters and AOML purchased 60 drifters, for total NOAA contribution of 1000 drifters to the JCOMM *"Global Surface Drifting Buoy Array"*.

Enhanced Data Sets and Publications

Since September of 2004, there were 24 requests for enhanced drifter velocity data sets. Sharon Schnider at Moana Consulting, Honolulu, who works for JIMO under a personnel services contract prepared and distributed these data. The drifter peer-reviewed publication list was upgraded in October 2004, with a total of 234 publications since 1984: (http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html).

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2. Surface Drifter Program

Silvia Garzoli, Bob Molinari and Rick Lumpkin

NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

The primary objective of the AOML drifter component of the Ocean Observing System is to provide oceanographic data needed to initialize the operational seasonal-to-interannual (SI) climate forecasts prepared by NCEP. Specifically, AOML manages a global drifting buoy network that provides sea surface temperature (SST), near surface (mixed layer) currents, air pressure and wind data needed to (a) calibrate SST observations from satellite; (b) initialize SI forecast models; and (c) provide nowcasts of the structure of global surface currents. Global drifter coverage is required as present forecast models simulate not only Pacific conditions but also global conditions to improve prediction skill. Secondary objectives of this project are to use the resulting data to increase our understanding of the dynamics of SI variability, and to perform model validation studies, in particular in the Atlantic Ocean. Thus, this project addresses both operational and scientific goals of NOAA's program for building a sustained ocean observing system for climate.

Atlantic Drifters

The main objective of this program is to fill gaps in the observational network, in order to accurately describe the basin-scale Atlantic current and SST seasonal to interannual variations. This program was started in 1998 to address the data coverage deficiency in the tropical and subtropical south Atlantic (20°N to 40°S).

Large-scale SST distributions drive the response of the climate in the tropical Atlantic sector, and over land areas as distant as the southern and eastern Unites States. In spite of its importance, no dynamical model has successfully predicted tropical Atlantic SST one-to-several seasons in advance. The current generation of coupled ocean-atmospheric models cannot reproduce, much less predict, the SST in the tropics. A recent comparison of 23 GCM results (Davey et al., 2002) concentrated on simulated fields from the tropical oceans (i.e. SST, zonal wind stress and upper layer depth averaged temperature). In the Atlantic Ocean, discrepancies between the model and observed mean states were dramatic. Specifically, in the equatorial Atlantic, the simulated meridional temperature gradient was wrong, with cold temperatures in the west and warm temperature in the east (Figure 4, Davey et al., 2002[1]). Furthermore, the variability of the subtropical Atlantic and its interaction with the tropics is far from understood. This is primarily due to the paucity of data that for years has been mainly collected in the major commercial lanes. SST products are considerably deficient in the center of the south Atlantic basin and between 20°S to 40°S. A recent paper (Kushnir et al., 2003[2]) demonstrated that the variability of the intertropical convergence zone (ITCZ) is highly sensitive to changes in SST gradients within the broader tropical Atlantic region, particularly in the meridional direction south of the tropics and during boreal spring. To better understand this variability, it is necessary to improve SST products in the South Atlantic. The development and future success of such models will depend on understanding the processes driving SST changes and providing products based on observations that models can attempt to simulate.

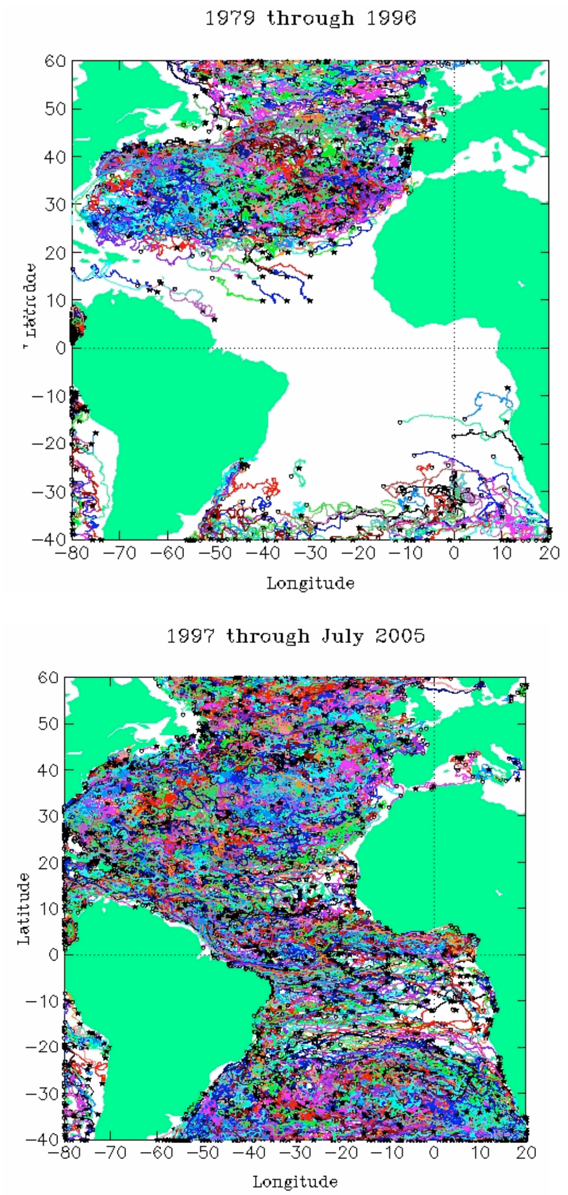

Figure 1. Evolution of the Atlantic surface drifter array. Top: trajectories of drifters deployed in or entering the region from 1979 through 1997 (18 years). Bottom: trajectories of drifters deployed in or entering the region, funded under the Atlantic (60°N - 40°S) Drifters program from 1997 through July 2005 (8.6 years).

As a result of this program, drifter data coverage in the tropical Atlantic Ocean has increased dramatically. Results can be seen in Figure 1, showing data coverage during the first 18 years of the Global Drifter Program (1979 to 1996) and since the Atlantic drifters program was started in 1997. A few gaps remain in areas of difficult access (like the South Eastern Atlantic) or fast dispersion (eastern Tropical Atlantic) but plans are to fill up these gaps in the next years.

Addressing NOAA's Program Plan

This project provides critical data for initializing seasonal to interannual forecasts. In addition, this program is a direct component of NOAA's Program Plan for building a *Sustained Observing System for Climate.* On September 18, 2005, the Global Drifter Array reached the goal of 1250 drifters worldwide, becoming the first fully implemented component of the Sustained Observing System for Climate. Future efforts will focus upon achieving and maintaining the required 5°x5° resolution of the drifter array.

Management in Cooperation with International Panels

The GOOS Center and its integral component, the Global Drifter Program (GDP), is a participating member of JCOMM and JCOMMOPS. Both the GDP and GDC – Data Assembly Center (DAC) are represented annually at the WMO/IOC Data Buoy Cooperation Panel (DBCP) and Joint Tariff Agreement (JTA) meetings. Participation on these international panels provides an important mechanism for integrating and coordinating with other national or regional programs which, in the long run, improves our national climate mission by making more efficient and effective use of available resources.

Responsible institutions

The GOOS Center located within the Physical Oceanography Division at AOML manages and operates the Global Drifter Program (GDP). The GDP is closely aligned with the Scripps Institution of Oceanography, SIO, for the procurement of Drifting Buoys. The GDP utilizes the National Weather Service Global Telecommunications System (NWSGTS) gateway for the real-time distribution of data and the National Oceanographic Data Center (NODC) and Marine Environmental Data Services (MEDS) for the archival of delayed mode data. The data are placed on GTS for operational use by Service Argos. AOML, under the direction of Mayra Pazos, quality controls and processes these data to quarter - day intervals and on six-month intervals sends to Marine Environmental Data Service (MEDS)/ Canada for archival and distribution.

Interagency and international partnerships

Drifters are launched using the AOML/GOOS infrastructure of NOAA interagency and international partners. Specifically, participation on the Data Buoy Cooperation Panel (DBCP) increases deployment opportunities.

FY 2005 PROGRESS

Performance Statistics

The Global Surface Drifter program is the first component of the Ocean Observing system that reached completion; 1250 active drifters by September 2005.

Instrument/platform acquisitions for fiscal year and where equipment was deployed

Operations

Operational Drifters for the Global Drifter Center are purchased by SIO. Drifting Buoys are deployed globally, in all four oceans (Pacific, Atlantic, Indian and Southern).

Atlantic Drifters

Drifters for the Atlantic program are purchased by AOML. During FY05, 101 buoys were deployed within the tropical Atlantic (20°N – 20°S), and *53* SVP buoys (*7* upgraded with barometers) were deployed in the subtropical south Atlantic (20°S- 40°S).

Number of deployments – compare to the previous year.

	FY04	FY05
Worldwide	**633**	**1057**
Atlantic (20N – 40S)	**124**	**154**
Rest of World	**509**	**903**

Percentage data return for fiscal year and 'lifetime' statistics – compare to the previous year

The following statistics are for the global array, and includes the Atlantic drifters: Before December 2004, data acquisition – including Sea Surface Temperature (SST) observations and position fixes – were received by two of the Polar Orbiting Environmental Satellites, averaging six (6) data points per day per drifting buoy. In late 2004 the Joint Tariff Agreement negotiated the use of all four satellites in the present constellation ("Multi-satellite processing"). Since mid-December 2004, we have been receiving approximately 16—20 data points per day per buoy. As the total global array is maintained at 1250 drifters, we anticipate approximately 22,000 SST observations per day.

Measurements and Data

Measurements taken, where data are stored, data distribution, availability and access to data

Observations collected include: position data, sea surface temperature (SST), some sea surface barometric pressure, some wind speed and direction. Data are stored at the GOOS Center in the Global Drifter Program's Data Assembly Center (DAC). Real time data are transmitted via Argos transmitters and distributed via the Global Telecommunications System (GTS) by Service Argos and available to everyone. The delayed mode and scientifically quality controlled data are available via access to web, ftp or personal communication with the DAC within two months of collection and a copy of the data are archived at the Marine Environmental Data System (MEDS).

How data are currently being used and shared

Drifter data are used in circulation research among several national and international oceanographic institutions. SST data are used among several national and international centers for environmental prediction (i.e. NCSP, US Navy, European Community Center for weather forecast, British and French Meteorological Offices, etc.), for ENSO monitoring and prediction and to initialize climate models. There are no restrictions on sharing this information as it is distributed in real time on the GTS.

Where the data are archived

Drifter data are archived at the GOOS Global Drifter Program Data Assembly Center (DAC) and at the Marine Environmental Data Service (MEDS) in Canada.

Anticipated and unanticipated project costs

Drifter costs are declining because of improved design changes, but shipping costs have increased due to late funding which required the use of air shipping rather than the less expensive ground shipping.

Problems encountered

1. Due to war related issues, the cessation of US Navy air deployments will continue. As a consequence, all deployments are made now from ships. This limits our capability to seed regions not visited by ships (VOS or research vessels).

2. Drogue on-off status is determined from the submergence or tether strain sensor. For an increasing number of drifters, these data are extremely noisy, ambiguous or faulty such that drogue status

is uncertain. We have been communicating with manufacturers to resolve this issue. For some manufacturers, this problem has been resolved to our satisfaction; with others, it is presently being addressed by reengineering (at the manufacturer level) and by additional processing (at AOML) to aid in detecting drogue loss.

Logistical considerations

We are very proud that a primary goal of the Global Drifter Program, reaching an array size of 1250 drifters, has been achieved this year. However, to maintain this number – and ultimately to achieve the requirement of 5ºx5º resolution – is going to be a challenge. The program is based on deploying the drifters through Voluntary Observation Ships and research vessels available wherever there is a gap in the nominal 5ºx5º array. This limits our capability to fill gaps not occupied by either of these vessel types.

We are addressing these challenges with a two-pronged strategy. First, we are actively seeking new ships to participate in the VOS program. For example, this year AOML has initiated drifter deployments from the MV *Explorer*, the Semester At Sea vessel that circumnavigates the globe every 100 days. Second, we are developing tools to predict the array coverage, in order to anticipate and plan for gaps before they develop.

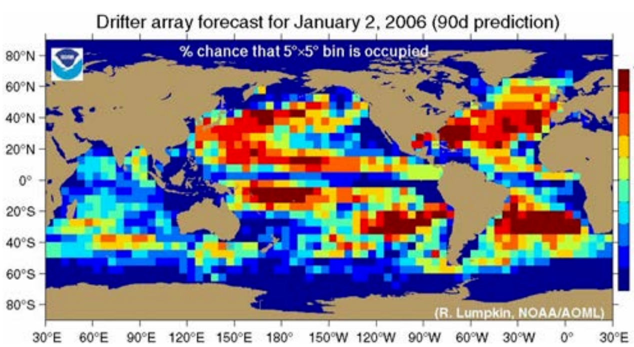

Figure 2. 90 day forecast of drifter coverage, based on present coverage and previous Lagrangian history of drifters. Colors indicate the percent chance that there will be at least one drifter in each 5ºx5º box.

An example is shown in Fig. 2. This tool has been made publicly available at http://www.aoml.noaa.gov/phod/dac/dacdata.html.

Analysis and Research Highlights

Scientific Findings

<u>*Atlantic Drifters:*</u> The tropical Atlantic surface drifting buoy observations were used to determine time-mean near-surface currents and their seasonal variations. As a consequence of the considerable increase in data coverage due to this program and a new analysis technique developed for the data (Lumpkin and Garraffo, 2005), the major pathways of near-surface currents are now resolved at unprecedented detail (Figure 3). An analy sis of the currents' seasonal variations (Lumpkin and

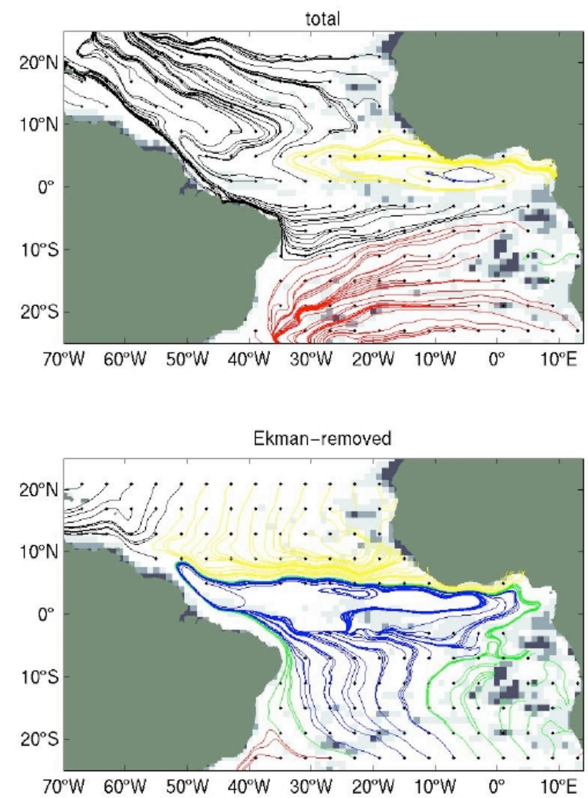

Figure 3. Pathways of advection from time-mean currents derived from surface drifter observations and visualized by integrating the currents from "release points" (black dots; see Lumpkin and Garzoli, 2005 for more details). Top: advection by total currents, including the wind-driven Ekman flow. Bottom: advection by the Ekman-removed flow.

Garzoli, 2005) reveals how northern and southern hemisphere fluctuations are "communicated" via the equatorial gyre route. Ongoing extensions of this study, also heavily dependent upon the drifter observations, are examining the distribution and possible rectification of mesoscale variability and are providing estimates of the role of lateral heat advection in modulating/

controlling observed SST variations.

A monthly climatology of near-surface currents and SST, derived from the drifter observations using the methodology of Lumpkin and Garraffo (2005), has been made available by the Drifting Buoy Data Assembly Center at http://www.aoml.noaa.gov/phod/dac/drifter_climatology.html.

Via OCO funding for analysis efforts, AOML is evaluating surface current measurements by the Global Ocean Observing System on a quarterly basis (see http://www.aoml.noaa.gov/phod/soto/gsc/index.php). This includes both drogued surface drifters and moored current meters, and quantifies how well the system is satisfying the GOOS/GCOS requirements for surface currents: 2 cm/s accuracy, at least one sample per month per 600 km box. A goal of this effort is to address gaps using satellite observations of sea height anomaly and winds, and quantify the global bias in satellite-derived surface currents as a function of the Global Drifter Array coverage.

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3. Global Drifter Program - Fabrication of 22 Hurricane Thermistor Chain Drifters

Peter Niiler
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La Jolla, CA

PROJECT SUMMARY

Project Rationale: Improvement of Hurricane Strength Analysis and Predictions

In the hurricane seasons of 2003, 2004 and 2005 NOAA supported at JIMO the construction and air-deployment of drifting buoys in front of hurricanes utilizing the 53rd Air Force Reserve "*Hurricane Hunter Squadron*." These drifting buoys measured ocean temperature, wind speed/direction, and barometric pressure on the SVP-W(wind) drifter; a total of 64 SVP-W buoys were successfully deployed in front of 3 category 4 Hurricanes (Fabian, Frances and Rita). Few other sea surface measurements in hurricanes are available to the NOAA National Hurricane Center (NHC) because ships avoid hurricanes and intense hurricanes generally destroy moored data buoys. Also, because the drifters were dropped directly in the path of hurricanes, measurements were made through the maximum wind speed core of the hurricanes, whereas moored buoys are not generally in their direct path. These data have been processed and are available from:
http://www.cora.nwra.com/~morzel/drifters.fabian.html
http://www.cora.nwra.com/~morzel/drifters.frances.html
http://www.cora.nwra.com/~morzel/drifters.rita.html

The focus of new ocean observations under hurricanes is on the requirement of the NHC to improve hurricane strength predictions. Hurricanes gain strength from the heat energy in the upper ocean – this energy potential cannot be measured accurately from satellites, only from data buoys. In 2005, Dr. Niiler and his group developed a new capability to add rugged "thermistor chains" to the drifting buoys for measurement of the upper ocean thermal energy content and eight of these were deployed in the path of Rita. Presently NOAA has resources sufficient to build eight hurricane drifters per year; this is enough for only two hurricanes in research mode. This supplemental task adds resources to build and deploy an additional 22 hurricane drifters per year, for a total of 30 data buoys -- enough for five hurricanes in operational mode.

FY2005 PROGRESS

Autonomous Drifting Ocean Station (ADOS) Drifter Deployments in Hurricane "*Rita*"

The ability to air-deploy drifters with operating data chains below the surface into hurricanes is a new development in ocean sciences. On September 21, 2005 the "53rd *Hurricane Hunter Squadron*" air-deployed 20 drifter containers in front of the projected path of Hurricane "*Rita*". All 20 drifters began data transmissions correctly after deployment and survived the passage of *Rita*. Twelve of the drifters were SVP-W and eight were ADOS (Figure 1). The deployment pattern (solid dots) and the subsequent 7.1 days of drifter tracks are displayed on Figure 2 that shows that most were caught in a *Loop Current-Warm Core Ring*.

The projected path of Rita (dotted green line) at the time of deployment was to take the center of *Rita* to the left side of the array, an ideal case for the study of the interaction of the hurricane with the ocean. But the actual path of Rita (solid green line) was to the right of the array. Drifter #45 experienced the full force of the hurricane winds. From the SST record of #45 (Figure 3) it appears that the SST cooled by 2.3ºC before the Center of Rita passed over this drifter. Tropical storm strength winds in the northeast quadrant of Rita were sufficient to cause significant ocean vertical mixing before the arrival of hurricane strength winds. In effect, a large part of the right side of Rita was traveling over its own SST cold wake. This kind of new detailed knowledge of the interaction of the hurricane and the ocean is required to improve the realism of hurricane prediction models and can be acquired only with targeted drifting buoys.

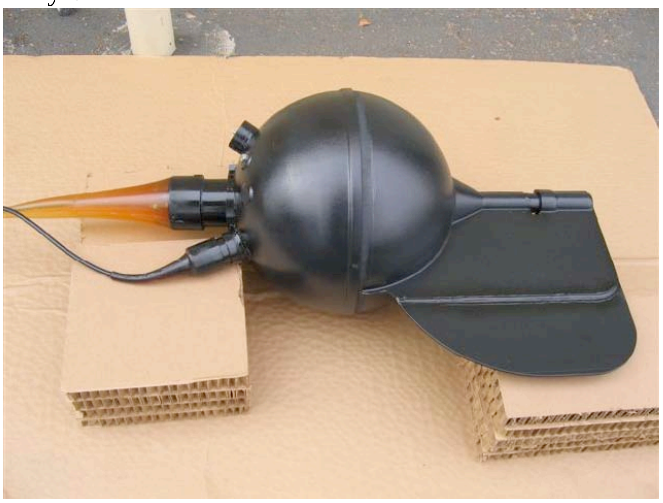

Figure 1. Photograph of the surface float of a SVP-W wind drifter that is attached to a thermistor chain, to form an ADOS drifter. The wind speed is determined from ambient noise with a hydrophone whose cable is protruding at an angle from the bottom of the float and the wind direction is determined from conditionally sampling the vane.

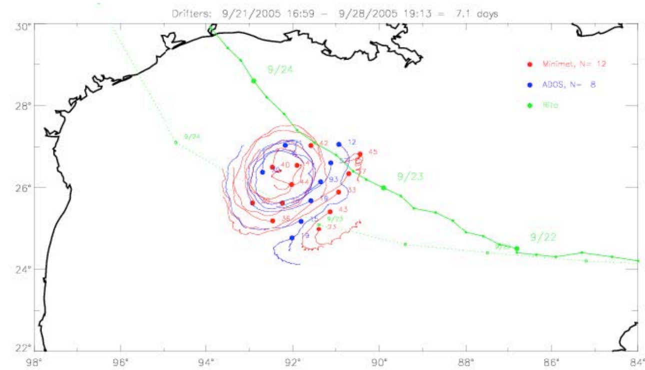

Figure 2. The initial deployment pattern (solid dots) of SVP-W drifters (red) and ADOS drifters (blue) in front of the projected path (dotted green). Displayed are also the actual path of Rita (solid green) and the subsequent 7.1 days of drifter tracks after deployment.

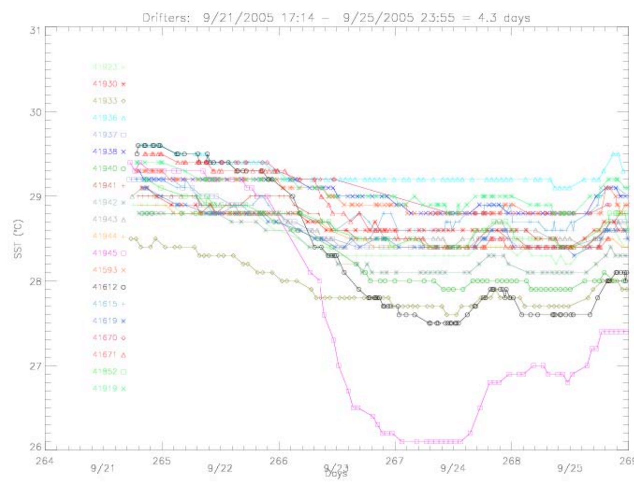

Figure 3. The SST observations from drifters deployed in front of the projected path of Hurricane Rita (Fig.2). The magenta observations of drifter #45 shows that a 3.2ºC SST change occurred by day 9/26.9/05 at which time hurricane strength winds had not reached drifter #45 (Fig.2).

1. An Indian Ocean Moored Buoy Array for Climate

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PROJECT SUMMARY

This contribution to NOAA's effort to “Build a Sustained Ocean Observing System for Climate” supports NOAA’s strategic plan goal to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond,” by maintaining and expanding the fledgling Indian Ocean moored buoy array initiated in the last year (FY 2005). The array is part of a multinational effort within the context of the Climate Variability and Predictability (CLIVAR) research program to improve understanding of the Australian-Asian monsoon and its far field impacts. Management of this array is consistent with the "Ten Climate Monitoring Principles". Program oversight at the international level is through the CLIVAR/GOOS Indian Ocean Panel (IOP) and the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel (TIP). A web site for data display and access has been developed and is undergoing beta testing.

Background

The US Climate Change Science Program has identified the critical need for the federal government to begin delivering regular reports documenting the present state of the climate system. As stated in the *US Climate Change Research Initiative* (CCRI, 2002), long-term monitoring systems are the foundation for research, modeling, and informed decisions. Yet an observing system capable of accurately documenting the full range of climate variability and change does not presently exist, especially for the oceans.

Much of the natural variability observed in the climate system originates in the tropics where heat from the sun enters the ocean. This heat is exported to higher latitudes on long time scales to moderate the Earth’s mean climate. On shorter interannual to decadal time scales, ocean feedbacks to the atmosphere influence patterns of global weather variability through teleconnections such as those associated with El Niño and the Southern Oscillation (ENSO). The advanced understanding of the role of the tropics in forcing mid-latitude weather and climate was gathered primarily through the observations of the tropical moored buoy array (TAO/TRITON) in the Pacific. A similar pilot array in the Atlantic basin (PIRATA) now offers the potential of even better understanding, improved forecasts, and improved ability to discern the causes of longer term changes in the oceans and their remote impacts over the US. The addition of an Indian Ocean array completes the moored component of a tropical ocean observing system.

The Indian Ocean influences the dynamics of the Indian and Asian monsoons. It also remotely affects the climate over the US and North America via monsoon-ENSO interactions and via atmospheric intraseasonal oscillations which are spawned over the Indian Ocean. The Indian Ocean is much less well sampled than either of the other two tropical basins however, resulting in serious limitations in the ability to predict seasonal-to-interannual climate variability. Thus, international planning efforts assign a high priority to establishing a comprehensive *in situ* observing system in the Indian Ocean as part of the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and the World Climate Research Program’s Climate Variability and Predictability (CLIVAR). As in the two other tropical basins, a broad scale Indian Ocean moored buoy array will form the cornerstone of systematic *in situ* ocean measurement efforts designed to improve description, understanding, and prediction of large ocean-atmosphere interactions and their influence on regional and global climate.

The goal of this effort is to develop a moored buoy array in the tropical Indian Ocean in concert with other observing system components such as the Argo floats, surface drifters, SOOP measurements, times series reference stations, tide gauges, and satellite remote sensing. Coordination at the international level is through the newly formed CLIVAR/GOOS Indian Ocean Panel and the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel. In addition to providing data for understanding and forecasting physical climate variations, moorings of the array can provide platforms for supporting instrumentation to measure carbon dioxide and other parameters essential for understanding the global carbon balance, biogeochemical cycles, and marine ecosystem dynamics. Thus, the array will support the development of improved climate analysis and prediction products of use to NOAA managers, policy makers, and the general public.

The ATLAS moorings measure winds, air temperature, relative humidity, precipitation, shortwave radiation, sea surface temperature and salinity, subsurface temperature at 11 depths in the upper 500 m, subsurface salinity at 5 depths in the upper 100 m, ocean pressure at 2 depths, and mixed layer velocity at 10 m depth. The equatorial site at 80.5°E is enhanced with additional subsurface temperature, salinity, velocity measurements, plus longwave radiation and barometric pressure to make it compatible with the OceanSITES time series reference station sampling requirements (http://www.oceansites.org). Because of concerns about elevated drag on the moorings due to strong Wyrtki Jets along the equator, this mooring also included a newly designed load cell with Iridium telemetry.

FY 2005 PROGRESS

The first meeting of the CLIVAR/GOOS IOP was held in Pune, India, in February 2004. The PI of this proposal is a member of the IOP and lead the effort to develop a draft plan for an Indian Ocean moored buoy array. The proposed array includes 38 surface moorings, 8 of which would have full air-sea flux measurement capability, and 5 subsurface ADCP moorings (Figure 1). Two of the surface moorings sites and one of the ADCP sites have already been occupied by JAMSTEC along 90°-95°E (Figure 2). A full discussion of

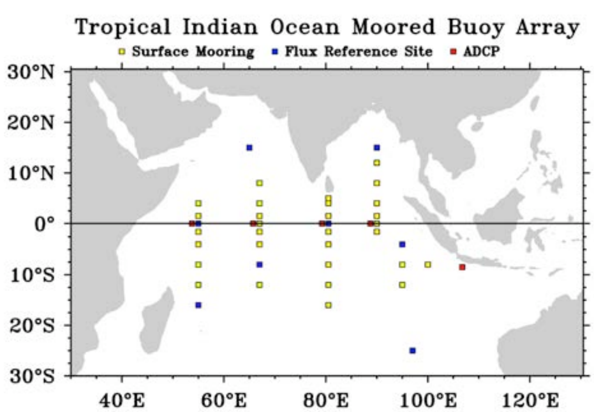

Figure 1. Proposed Indian Ocean Mooring Array.

the scientific rationale for the array, as well as other elements of a proposed Indian Ocean observing system for climate, can be found in the IOP strategy document at ftp://ftp.marine.csiro.au/pub/meyers/Implementation Plan/. This document was finalized following the second meeting of the Indian Ocean Panel, which the PI attended in Hobart, Australia during 30 March-2 April 2005.

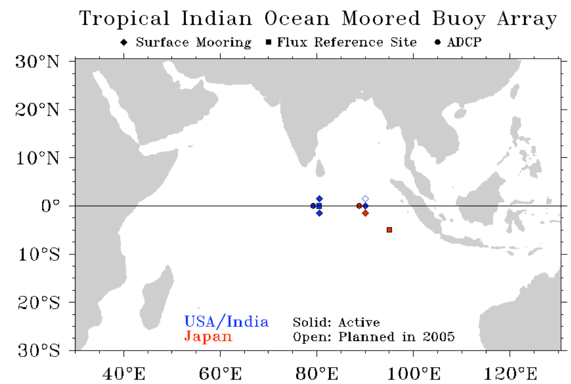

Figure 2. Active and planned moorings in 2005.

As detailed in last year's report, the PI wrote a proposal with scientists from India's National Institute of Oceanography (NIO) to seek several days of ship time for the deployment of ATLAS moorings from the Indian ORV Sagar Kanya. The cruise took place from 9 October to 17 November 2004 with two PMEL technicians aboard. In all, 8 days of ship time were provided for PMEL mooring operations. Three ATLAS moorings were deployed along 80.5ºE at 1.5ºN, 0º, and 1.5ºS, with the 0° ATLAS instrumented as a full flux reference site. One subsurface ADCP mooring was deployed near the 0°, 80.5°E ATLAS and a fourth ATLAS was deployed at 0°, 90°E. Part of the hardware and instrumentation for these moorings came from inventory accumulated as part of the PACS/EPIC enhanced monitoring program along 95°E which ended in 2003.

The ATLAS moorings measure winds, air temperature, relative humidity, precipitation, shortwave radiation, sea surface temperature and salinity, subsurface temperature at 11 depths in the upper 500 m, subsurface salinity at 5 depths in the upper 100 m, ocean pressure at 2 depths, and mixed layer velocity at 10 m depth. The equatorial site at 80.5°E is enhanced with additional subsurface temperature, salinity, velocity measurements, plus longwave radiation and barometric pressure to make it compatible with the OceanSITES time series reference station sampling requirements (http://www.oceansites.org). Because of concerns about elevated drag on the moorings due to strong Wyrtki Jets along the equator, this mooring also included a newly designed load cell with Iridium telemetry.

The deployment of PMEL moorings on the ORV Sagar Kanya generated considerable excitement in the oceanographic community interested in observing system development. Even before the cruise had ended, NOAA Administrator VADM Lautenbacher was showcasing real-time data from the moorings in his keynote address to the Oceans ‘04 International Conference in Kobe, Japan in early November. Success of the cruise provided VADM Lautenbacher with the opportunity to highlight a very recent example of international cooperation in the development of Global Earth Observing System of Systems (GEOSS) of which the Indian Ocean observing system is a component. A report on the development of the Indian Ocean Observing System and the deployment cruise was featured in the OAR web-based newsletter Spotlight file://localhost/(http://www.research.noaa.gov/spotlite/archive/spot_taoarray.htm).

An example of real-time data from the ATLAS mooring 0°, 80.5°E (Figure 3) shows variability in winds, temperatures, and currents on a variety of time scales. October to December is the so-called Monsoon Transition season (between Southwest and Northeast Monsoons).

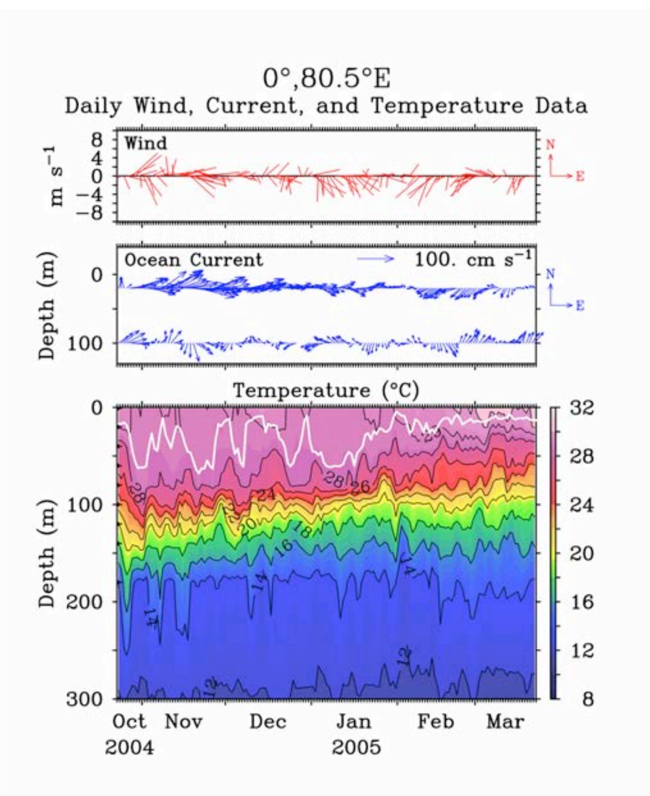

Figure 3. Winds, currents, temperatures, and mixed layer depth based on density (in white) at 0°, 80.5°E.

Winds are highly variable and mostly westerly during this time, unlike the more steady trades in the Atlantic and Pacific. Near-surface currents (20 m) are eastward until late January because of this westerly wind forcing. The 20 m currents reverse when the zonal winds reverse during the development of the Northeast Monsoon in February. Mixed layer depth shoals and stratification in the thermocline weakens when the zonal winds reverse. Remarkably, when easterlies develop in February, sea surface temperatures warm rather than cool as one might expect based on easterly trade wind forced variability in the Atlantic and Pacific. Note also the pronounced week-to-week variability in thermocline temperatures and mixed layer depths associated with the variable winds and currents.

Data return has suffered as a result of fishing vandalism (Figure 4). Of the four ATLAS moorings deployed in

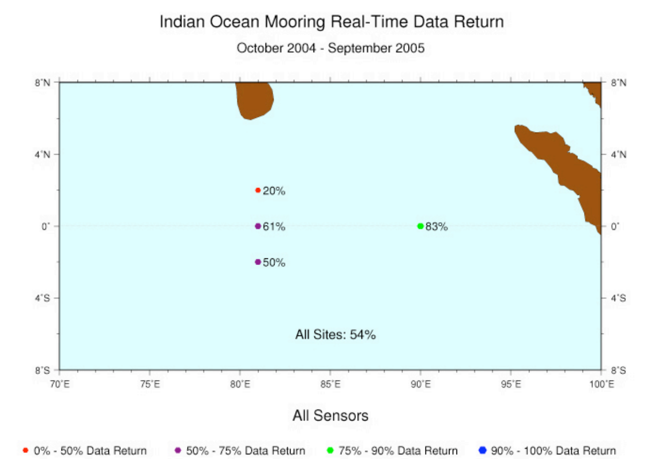

Figure 4. Indian Ocean ATLAS real-time data return for FY 2005

October-November 2004, three have stopped transmitting (Table 1) and total data return for FY 05 is 54%
.

Buoy Location	Date Deployed	Date of Last Transmission	Days Transmitting in FY2005
1.5N°, 80.5°E	10/20/2005	1/22/2005	94
0°, 80.5°E	10/22/2005	8/13/2005	295
1.5S°, 80.5°E	10/29/2005	5/09/2005	192
0°, 90°E	11/9/2005	N/A	326

Table 1. Deployment locations, dates, and data transmission information for Indian Ocean ATLAS moorings

The mooring deployed at 1.5°N 80.5°E stopped transmitting in January 2005 after quickly moving 35 nm and was presumably taken aboard a fishing vessel. A cruise of the *ORV Sagar Kanya* along 80.5°E in May 2005 sighted the 0° and 1.5°S moorings, though the latter was badly damaged with lines from a fishing boat attached. The mooring at 0°, 80.5°E subsequently stopped transmitting in August 2005

In terms of negotiating regional partnerships to help implement and sustain the moored buoy array, the PI provided graphics and advice to NOAA's Climate Program Office and Office of Climate Observation in preparation for the IOGOOS-3 meeting held in Bali, Indonesia during 9-12 August 2005. This meeting afforded the opportunity for high-level discussions between NOAA and parties representing institutions in India, Indonesia, and China for the development of an Indian Ocean Observing System. A key issue from the point of view of the moored buoy array is finding enough ship time to carry out necessary servicing. Within NOAA prior to the meeting, we established a framework for discussing partnerships based on the following principle: NOAA would offer to provide equipment, technical support, and capacity building while partners in the region (e.g. India, Indonesia, China) would contribute, rather than require chartering of, ship time to service the array. It appears that this principle was agreed to based on reports from participants at the meeting.

2. Pilot Research Moored Array in the Tropical Atlantic (PIRATA)

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PROJECT SUMMARY

This continuing project maintains the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) as part of NOAA's effort to "Build a Sustained Ocean Observing System for Climate". PIRATA is a joint effort between the U.S. (NOAA/PMEL), France (Institut de Recherche Scientifique pour le Développement en Coopération [IRD] and Meteo-France), and Brazil (Instituto Nacional de Pesquisas Espaciais [INPE] which is the Brazilian space agency and Diretoria de Hidrografia e Navegacao [DHN] which is the naval hydrographic service). PIRATA supports NOAA's strategic plan goal to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond." It also underpins Climate Variability and Predictability (CLIVAR) research efforts on tropical Atlantic climate variability. Management of PIRATA is consistent with the "Ten Climate Monitoring Principles". Program oversight at the international level is through the PIRATA Scientific Steering Group and the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel (TIP). A web site containing comprehensive information on the program can be found at http://www.pmel.noaa.gov/pirata/

France and Brazil provide ship time and support for equipment shipments as part of a tri-lateral agreement to maintain the array. PMEL is charged with providing equipment, technical support for moorings and instrumentation, and support for data processing, dissemination, and display. France and Brazil also provide technician support at sea.

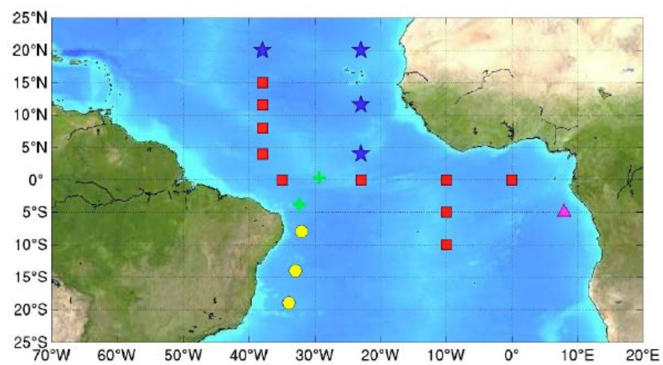

Figure 1. The Tropical Atlantic, showing the PIRATA backbone (red squares), automatic meteorological stations (green +), southwest extension (yellow circles), southeast extension pilot site (magenta triangle), and the proposed northeast extension (blue stars).

FY 2005 PROGRESS

Background

During FY 2005, the core PIRATA array was maintained in a 10-mooring configuration as agreed upon for the consolidation phase of the program (2001-2005). The consolidation phase itself, scheduled to end in February 2005, was extended for another year to February 2006 by mutual agreement of the supporting nations. It is likely that the agreement will be extended again for another year to allow for an orderly evaluation of PIRATA for operational oceanography and climate forecasting.

As in the Pacific TAO array, PIRATA primary variables include winds, air temperature and relative humidity, SST, subsurface ocean temperature and pressure. By design however, PIRATA also includes salinity at the surface and at 3 depths in the upper 120 m, shortwave radiation, and rainfall. In addition, three moorings were enhanced with temperature, conductivity and horizontal currents at 10 m and conductivity at 60 m to provide enhanced T/S vertical resolution and mixed layer velocity data. The three sites are the proposed flux reference sites at 15°N, 38°W; 0°, 23°W; and 10°S, 10°W.

The PIRATA array expanded in FY 2005 with three new moorings at 8°S, 30° 30'W; 13° 30'S, 32° 30'W; and 19°S, 35°W. INPE in Brazil sponsored this 'Southwest (SW) Extension" and PMEL provided 3 ATLAS mooring to INPE on contract to initiate the extension. Brazilian technicians, trained by PMEL in ATLAS mooring laboratory and field techniques, were responsible for the deployments (See "Training of Brazilian Technicians" Section below). This year NOAA will be responsible for providing replacement moorings under terms of the PIRATA MOU.

PMEL purchased equipment required to assemble 2 ATLAS moorings in FY 2005 for deployment in FY 2006 as part of an AOML-led effort to expand PIRATA into the Northeast Atlantic. A separate AOML-PMEL proposal to NOAA to support this work in the next 5 years will be submitted in FY 2006. A collaborative AOML-PMEL proposal for a NE Extension was also submitted to the PIRATA SSG for consideration in early October 2005.

PIRATA data are available from the PIRATA web site (http://www.pmel.noaa.gov/pirata/) and the TAO web site (http://www.pmel.noaa.gov/tao/). There are also mirror sites in France and Brazil. Collection, processing, and dissemination of shipboard CTD and ADCP data are the responsibility of France and Brazil.

Training of Brazilian Technicians

Three technicians from João Gualberto de Cerqueira Jr (INPE), Paulo Rogerio de Aquino Arlino (INPE), and Maria de Lourdes (U. Sao Paulo), received training at PMEL from 4-14 May May 2005. Subjects included the maintenance and calibration of ATLAS instrumentation, mooring design and preparation, and shipboard operations. Mr. Arlino participated on all, and Mr. de Cerqueira Jr, participated on some of the Brazilian PIRATA cruises in August and September 2005. The skills and knowledge acquired while visiting PMEL made it possible for INPE personnel to assume an increased level of responsibility on Brazilian PIRATA cruises. As a result, PMEL intends to decrease its staffing on future Brazilian cruises from 2 to 1 technician. We expect that Brazil will be responsible for servicing all future SW Extension cruises.

Ship Time and Sea Time

For PIRATA, 13 new ATLAS moorings were deployed on 3 cruises in FY 2005. A total of 90 sea days (27 on the French R/V Suroit. 38 on the Brazilian R/V Antares, and 25 on the Brazilian R/V Amorim do Valle) were required to service the array. PMEL personnel spent 38 person-days at sea on these cruises.

Moorings were deployed at the 5 easternmost PIRATA sites in May-June 2005 from the R/V Suroit, which was staffed entirely by technicians from IRD, as has been the norm for the past several years. Moorings were recovered from only 3 sites, as no moorings were found at 0º, 0º or 0º, 10ºW. The moorings at these sites had stopped transmitting in May 2004, presumably due to vandalism.

Four of the five westernmost moorings were deployed from the R/V Antares with participation of both PMEL and INPE personnel in July 2005. The mooring at 4º, 38º W was to have been deployed on the same leg, but a medical emergency and marginal weather cut the cruise short. This mooring and one of the SW Extension moorings were deployed in August from the R/V Antares by INPE technicians trained at PMEL ("Training of Brazilian Technicians" Section). The other two SW Extension moorings were deployed later in August-September by INPE from the R/V Amorin do Valle with the R/V Antares standing by. Damaged sensors and other mishaps during deployment from the R/V Amorin do Valle may indicate that procedures need to be refined, but the deployments were successfully completed as evidenced by the fact that good data are transmitting from all sensors.

Data Return

Real-time data return was 72% overall for FY 2005, 7% lower than for FY 2004. The decreased data return was in main due to the loss of 2 moorings in the Gulf of Guinea. PIRATA data return remains lower than Pacific data return for TAO/TRITON of 90%. The difference between the two basins relates to the greater susceptibility of the smaller PIRATA array to fishing vandalism and to a less frequent servicing schedule (one per year or less vs. twice per year for much of the Pacific). The lost moorings mentioned above were deployed in February 2004, stopped transmitting in May 2004, and not replaced until June 2005.

Real-time PIRATA data return by variable for FY 2005 (and for comparison, FY 2004) is shown below.

	AIRT	SST	T(Z)	WIND	RH	Rain	SWR	SAL	ALL
FY 2005	78	69	74	70	78	72	76	66	72
FY 2004	92	78	81	68	86	64	84	75	79

PIRATA Web-based Data Distribution

The TAO Project continues to update the content and functionality of its web site (http://www.pmel.noaa.gov/tao/). This site provides easy access to TAO/TRITON and PIRATA data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays. For FY 2005, a total of 3,874 separate user requests delivered 26,430 PIRATA data files. These numbers are up 36% and 95%, respectively from the year before.

Operational Use of PIRATA Data

PIRATA data are distributed via the GTS to centers such as NCEP, ECMWF, and Meteo-France where they are used for operational weather, climate, and ocean forecasting and analyses. PIRATA data placed on the GTS include spot hourly values of wind speed and direction, air temperature, relative humidity, and sea surface temperature. The volume of spot hourly values placed on the GTS increased by a factor of 2 in February 2005 as the result of switching to multi-sat Argos service. PIRATA moorings deployed in 2005 provided another doubling of GTS data by increasing the transmission schedule from 8 to 16 hours per day. Daily averaged subsurface temperature and salinity (added in February 2005) data are also transmitted on the GTS. Daily ftp transfers are made from PMEL to the CORIOLIS operational oceanography program in France. The MERCATOR program in France makes use of the CORIOLIS data base to generate operational ocean model based data assimilation products. PIRATA data are also available on the GODAE server in Monterrey, California.

Vandalism

Vandalism continues to plague portions of the PIRATA array. Data and equipment return are generally lower in regions of high tuna catch in the Gulf of Guinea, where data return for FY 2005 was 28%. Four of the 5 easternmost— PIRATA moorings (all but 10°S, 10°W) showed evidence of interaction with fishermen (fishing line, missing or damaged sensors, damaged buoys) when recovered in FY 2005.

Efforts to combat vandalism continue, though it is not clear they are making much impact. These efforts include distribution of information brochures to national fishing agencies, fishing boats in ports of call, and industry representatives, and have contributed to international efforts to decrease vandalism through the DBCP. The attractive RM Young wind sensor may be replaced with a less conspicuous sonic anemometer if tests of the latter prove encouraging and funding for system upgrades become available. Evaluation of field tested sonic anemometers is presently underway.

TAO Transition

In a memo dated 13 August 2002, the Deputy Directors for OAR and the National Weather Service instructed the directors of PMEL and NDBC to develop a plan for transferring PMEL operations to NDBC. The memo was in response to the Administrator of NOAA's endorsement of a recommendation by the NOAA Program Review Team that TAO mooring operations be consolidated with those at NDBC. After several iterations, the Deputy Administrator of NOAA formally approved a TAO transition plan in September 2004.

The PIRATA review, which is scheduled for 2006, will determine whether the array should continue as a permanent component of the Global Ocean Observing System (GOOS). Assuming a favorable outcome of the review process, it is expected that, beginning in FY 2007, PIRATA will begin transition from PMEL to NDBC for operation and maintenance.

3. NOAA's PIRATA Northeast Extension

Robert L.Molinari[1], Rick Lumpkin[1], Claudia Schmid[1], Michael McPhaden[2]

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[2]NOAA/Pacific Marine Environmental Laboratory, Seattle, WA

PROJECT SUMMARY

Tropical Atlantic Variability (TAV) is a complicated mix of atmospheric (i.e., West African Monsoon, Intertropical Convergence Zone, ITCZ, Trade Winds, African Easterly Waves, etc.) and oceanic (i.e., sea surface temperature, SST, coastal and equatorial upwelling, Tropical Instability Waves, etc.) phenomena, which interact on a range of spatial and temporal scales. These interactions have been shown to affect local, regional and basin-wide climate variability. The ability to simulate and ultimately predict these complex air-sea interactions and their larger-scale impacts on TAV is limited by the lack of quantitative understanding of the processes that couple the ocean and atmosphere and modeling and observational deficiencies. For instance, the migration and intensity of the ITCZZ is neither represented nor predicted accurately within existing models. However, such studies do suggest that there is strong coupling between the ITCZ and SST. Three hypotheses have been selected to "identify sources of and mechanisms that determine predictability" of TAV. These are: (1) Air-sea coupling processes are a potential source of predictability to be studied in the eastern tropical Atlantic; (2) The large-scale atmospheric and oceanic processes that control convection in the ITCZ are another source of potential predictability to be studied; and (3) The processes that control the impact of the Saharan Aerosol Layer on atmospheric and oceanic anomalies in the eastern Atlantic are another source of potential predictability in the region. These hypotheses are being tested by deploying three TAO-like moorings along 23ºW in the eastern tropical Atlantic and another along 35ºW.

Addressing NOAA's Program Plan

This project will provides critical data for initializing SI forecasts. The data resulting from this project will also address objectives 3 and 4 (i.e., the heat content and air-sea flux elements) of the OCO Program Plan.

Management in Cooperation with International Panels

The PIRATA project is coordinated by the PIRATA steering team made up of scientists from the three participating countries, U.S.A., Brazil and France. Dr. Rick Lumpkin of AOML has joined the steering team and will ensure that the Northeast Extension is managed in cooperation with the PIRATA group.

Responsible institutions

AOML is responsible for the general oversight of the project. PMEL works in collaboration with AOML to establish and maintain 4 sites in the NE tropical Atlantic as an extension of the PIRATA array. The work plan builds on support provided by OCO in FY05 to purchase an initial set of two moorings. PMEL is responsible for the reduction and transmission on the Global Telecommunications System of the resulting data. AOML and PMEL work cooperatively on the scientific analyses of the mooring measurements.

Interagency and International Partnerships

AOML works closely with the other members of the PIRATA consortium to ensure that all program protocols are being followed.

FY 2005 PROGRESS

Instrument/platform acquisitions for the fiscal year and where equipment was deployed: Two TAO moorings were constructed by PMEL with FY05 funds.

Number of AOML deployments by calendar year – compare to the previous year.

FY05- No planned deployments

FY06- Deployment of two moorings along 23ºW during the summer of 2006.

Percentage of data return for fiscal year: Data collection will begin in FY2006.

Measurements taken, where data are stored, data distribution, availability and access: Data collection will begin in FY2006.

How data are currently being used and shared: When data collection begins, observations will be transmitted in real time on the GTS and accessible on the PMEL TAO website.

Where the data are archived: Short term archiving will be at PMEL and AOML.

Logistical considerations: Thirty-five days of RON BROWN ship time has been allocated for this project during FY06. A request for similar ship time for FY07 has been submitted.

Research highlights:
Continued interactions with international scientists have demonstrated the importance of increased mooring activity in the tropical Atlantic. Specifically, AOML scientists are involved in planning of the African Monsoon Multidisciplinary Analysis project. The objectives of AMMA are to study the West African monsoon and it's associated offshore features (i.e., the atmospheric waves that can generate tropical storms and hurricanes). The planned location of the moorings in the Main Development Region for tropical cyclones will provide data to study interannual changes in the physical environment that affects atmospheric waves and their development into storms.

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4. Tropical Atmosphere Ocean (TAO) Array

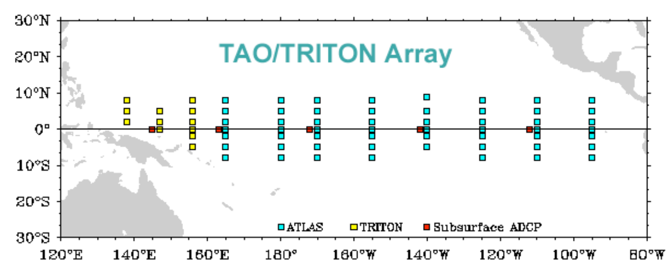
Landry Bernard
NOAA/National Data Buoy Center, Stennis Space Center, MS

PROJECT SUMMARY

FY 2005 funding to NDBC was expended to maintain the Tropical Atmosphere Ocean (TAO) array as part of NOAA's effort to "Build a Sustained Ocean Observing System for Climate." TAO is the U.S. contribution to the TAO/TRITON array, a network of moored buoys spanning the tropical Pacific Ocean maintained in partnership with the Japan Marine Science and Technology Center (JAMSTEC). TAO/TRITON supports NOAA's strategic plan goal to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond." It also underpins Climate Variability and Predictability (CLIVAR) research efforts on El Nino/Southern Oscillation (ENSO). Program oversight at the international level is through the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel (TIP). A web site containing comprehensive information on both programs can be found at http://www.pmel.noaa.gov/tao/

FY 2005 was the fifth full year of the combined TAO/TRITON array and the partnership with JAMSTEC is working well. NOAA maintains the portion of the array between 95°W and 165°E, while JAMSTEC maintains sites between 156°E to 138°W. JAMSTEC added three moorings along 130°E for its own purposes in FY 2002, though these moorings complement those of the TAO/TRITON array proper. Basic measurements from ATLAS and TRITON buoys are transmitted on the GTS and are merged into a unified data set available on the World Wide Web at PMEL (http://www.pmel.noaa.gov/tao/).

PMEL is responsible for maintaining 55 ATLAS sites at and east of 165°E. At four of these sites (165°E, 170°W, 140°W, 110°W along the equator) current meters are attached to the ATLAS mooring lines and a nearby subsurface ADCP mooring is deployed. An ADCP mooring is maintained by JAMSTEC at 0°, 147°E. During the past year, the TAO Project deployed 64 ATLAS moorings and 4 subsurface ADCP current meter moorings in the tropical Pacific. The number of ATLAS deployments exceeds the number of ATLAS sites in the array because of mooring system failures or losses during the year, because some sites (like the equatorial current meter mooring sites at 110°W and 140°W) are turned around regularly on a 6-month rather than 12-month schedule and because cruise schedules are such that some moorings are deployed for slightly shorter than their 12-month design lifetime.



FY 2005 PROGRESS

TAO/TRITON Array

TAO Project Highlights

At present, TAO/TRITON data indicate weak El Niño or neutral conditions in the tropical Pacific. Forecast models, many of which depend heavily on TAO/TRITON data for initialization, suggest that near neutral conditions will continue into early 2006.

Ship Time and Sea Time

In FY 2005, 255 days at sea were required to support the TAO portion of the TAO/TRITON array (220 days on the Ka'imimoana and 35 on the Ron Brown) a total of 620 PMEL person days at sea (number of people times days at sea) in support of TAO field work were required. For comparison, 264 days at sea (221 days on the Ka'imimoana and 43 on the Ron Brown) and a total of 688 PMEL person days at sea in support of TAO field work were required during FY 2004.

As part of the TAO Transition, NDBC participated in 156 NDBC person days at sea (number of people times days at sea) in support of getting familiar with TAO field work. The 156 NDBC person days were both government and contractor personnel as well as engineers and technicians.

Data Return

Percentage real time data return for primary TAO variables integrated over all 55 sites for FY 2005 was as follows:

	AIRT	SST	T(Z)	WIND	RH	ALL
FY 2005	89	91	92	86	87	91
FY 2004	88	88	89	76	89	88

Real time data return for the entire TAO/TRITON array (including JAMSTEC TRITON moorings) was 90% for primary variables. Data return from the most recently recovered PMEL ADCPs in FY 2005 was effectively 100% at the four equatorial sites.

For comparison, ATLAS data return from FY 2004 is also shown in the above table. Wind sensor data return has historically been lower relative to other sensors, due to a higher potential for vandalism, and relatively higher sensor failure rate. Modifications to sensors deployed in CY 2005 which were intended to improve sensor reliability appear to have positive results, in that wind sensor data return increased by 10% in FY 2005 relative compared to FY2004.

After mooring recovery, data recorded on board the buoy are available and may augment data not available in real time. For this reason, combined delayed mode and real time data return are typically a few percent higher than real time data return.

In addition to primary ATLAS variables, additional measurements were made as part of research efforts supported by other programs. In FY 2005 these measurements include ocean velocities, rain rate, salinity, short wave, and barometric pressure. These data are distributed via TAO web pages. TRITON sites also measure rain rate, shortwave radiation, and ocean velocity (at 10 m).

Shipboard Measurements

CTD casts, and underway ADCP and thermosalinograph measurements, are conducted from mooring servicing cruises on the Ka'imimoana and Ron Brown. These data are an integral part of the TAO Project, providing in situ calibration checks on mooring sensor performance. They also provide hydrographic and current field information that helps to put the moored time series measurements into a broad scale hydrodynamic context. The data are a valuable resource for climate model development and climate analyses, and are frequently used together with moored times series data in scientific publications.

A total of 407 CTD casts were made on TAO cruises in FY 2005, which was a small increase over FY 2004 (400). The shipboard ADCP data are forwarded to, processed, archived, and distributed by Eric Firing and colleagues at the University of Hawaii. Underway sea surface salinity measurements are processed at PMEL, and then forwarded regularly to the IRD laboratory in Noumea for distribution (by CD-ROM) with other sea surface salinity data (http://www.ird.nc/ECOP/siteecopuk/cadres.htm).

Engineering – TAO Payload Technology Refresh

NDBC began technology refresh to upgrade the existing Tropical Atmosphere Ocean (TAO) array data logger hardware that replaces obsolete or unsupportable components with supportable replacement components. The upgrade, called the Advanced Modular Payload System (AMPS), incorporates mostly commercial, off-the-shelf components and sensors to replace custom design, taking advantage of miniaturization and lower power components where possible to reduce overall system power consumption. Because the AMPS data logger is a modular design, it has the capability for addition of expansion modules to provide compatibility with measurement sensors and systems on NDBC buoys and C-MAN stations and will be used on these stations for standard meteorological measurements and to add oceanographic measurement capability to some of these platforms. Progress on the TAO AMPS data logger technology refresh includes: Award of a contract in early June ’05; completion of a Requirements Review in late June ’05; completion of a Preliminary Design Review in mid-August ’05; and completion of a contract modification in late August ’05 to increase delivery quantities for FY 06 and add some sensor upgrades. The TAO AMPS data logger technology refresh project is on track to complete a Critical Design Review in early December ’05 and delivery of the first 3 production units for field testing by late February ’06.

Guest Investigator Research Projects Using TAO Moorings and TAO Cruises

The primary mission of the TAO/TRITON array is to provide real-time data for improved detection, understanding, and prediction of El Niño and La Niña. The primary function of the NOAA Ship Ka’imimoana is to service buoys of the TAO/TRITON array. However, the TAO Project Office actively promotes use of the Ka’imimoana and, when it is used for TAO cruises, the Ron Brown for other meritorious scientific investigations that are of relevance to NOAA’s mission. These projects are developed, funded, and lead by investigators from NOAA laboratories, other national research laboratories, and academia. Two categories of ancillary projects are described which are (a) ongoing and (b) one-time or for a limited number of cruises. An ongoing project is either planned or has been onboard already for several years. A list of PIs, their institutions and project titles are itemized below. The name of the ship from which the work is done (KA or BROWN) is indicated in parentheses.

Ongoing ancillary projects on TAO cruises for FY 2004:

Project, Principal Investigator, Institution (Ship)

- Underway CO2, Richard Feely, NOAA/PMEL (KA and BROWN)
- Turbulent flux measurements and wind profiler, Chris Fairall and Jeff Hare, NOAA/ETL (BROWN)
- Atmospheric monitoring, balloon radiosonde profiles, Nick Bond, NOAA/PMEL (BROWN)
- Carbon cycle, Michael Bender, Princeton University (BROWN)
- Dissolved Inorganic Carbon (DIC) Analysis, Andrew Dickson, Scripps Institution of Oceanography (KA)
- Argo float deployments, Greg Johnson, PMEL (KA)
- Global Drifter Program, Robert Molinari, NOAA/AOML (KA and BROWN)
- Iron limitation, Mike Behrenfeld, NASA/Goddard (BROWN)
- CO2 moorings, Chris Sabine, NOAA/PMEL (KA)
- Bio-optical measurement and nutrient analysis, Francisco Chavez, MBARI (KA)
- Haruphone mooring recoveries/deployments, Robert Dziak, NOAA/PMEL (BROWN)
- Tsunami/DART mooring recovery deployment at 8.5°S, 140°W, NOAA/NDBC (KA)
- Underway ADCP, Eric Firing, University of Hawaii (KA and BROWN)
- Underway pO2/pN2- Gas Tension device and O2 probe, Craig McNeil,
- University of Rhode Island (BROWN)
- O2, N2, Ar, CO2 underway sampling, Jan Kaiser, Princeton University, (KA)
- Nitrate and O2 isotope analysis, Patrick Rafter, Scripts Institution of Oceanography (KA)

One-time or limited-term ancillary projects on TAO cruises for FY 2005:

- Sea-Surface Skin Temperature Radiometer Intercomparison Study, Jeremiah Reynolds, RMRCO, (BROWN)
- W-Band Doppler Radar ,Virendra Ghate and Ieng Jo, University of Miami (BROWN)
- Membrane Inlet Mass Spec., Blake Sturtevant, Princeton University, (KA)
- Tuna Migration Study, Brittany Graham, University of Hawaii (KA)
- Lagrangian Float, Ren-Chieh Lien, Eric D’Asaro, University of Washington,(KA)
- Oxygen, Argon, and Nirtrogen Sample Collection, Steve Emerson, Univ. of Washington (KA)
- Equatorial Box Project, Michael Behrenfeld, Oregon State University (KA)
- Moored Mixing Measurements, Jim Moum, Oregon State University (KA)

TAO Project Web Pages

The TAO Project continues to maintain the content and functionality of its web site (http://www.pmel.noaa.gov/tao/). This site provides easy access to TAO/TRITON data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays. For FY 2005, TAO web pages received a total of 24,071,140 hits, an increase of 14% FY 2004 (21,016,647). Also during FY 2005, a total of 8,814 separate user requests delivered 85,546 TAO data files.

We had hoped to begin inclusion of TRITON salinities, radiation, rainfall, and currents to the TAO/TRITON web pages in FY 2005, but the development of a new TRITON Data Management System at JAMSTEC, which is necessary for the TAO/TRITON web page enhancement, is behind schedule.

Operational Use of TAO/TRITON Data

TAO/TRITON data are distributed to operational centers such as NCEP via the GTS. These data are used routinely in climate forecasting and analyses. The data are also used for weather and severe tropical Pacific storm forecasting. A weekly ftp transfer is routinely made to the NCEP coupled modeling project so as to ensure maximum ocean data availability for coupled model ENSO forecasts. TAO data placed on the GTS include spot hourly values of wind speed and direction, air temperature, relative humidity, barometric pressure, and sea surface temperature. The volume of spot hourly values placed on the GTS increased by a factor of 2 in February 2005 as the result of switching to multi-sat Argos service. TAO moorings deployed in 2005 provided another doubling of GTS data by increasing the transmission schedule from 8 to 16 hours per day. Daily averaged subsurface temperature and salinity (added in February 2005) data are also transmitted on the GTS.

Vandalism

Vandalism continues to plague portions of the TAO/TRITON arrays. Data and equipment return are generally lower in regions of high tuna catch in the eastern and western equatorial Pacific. In addition to partial mooring hardware and instrumentation losses, 6 complete moorings systems were confirmed lost in the Pacific due to the effects of vandalism and another 2 moorings may be lost, but not yet confirmed.

Efforts to combat vandalism continue, though it is not clear they are making much impact. These efforts include distribution of information brochures to national fishing agencies, fishing boats in ports of call, and industry representatives, and have contributed to international efforts to decrease vandalism through the DBCP. We may replace the attractive RM Young wind sensor with a less conspicuous sonic anemometer if tests of the latter prove encouraging and funding for system upgrades become available.

TAO Transition FY 2005 Accomplishments

In a memo dated 13 August 2002, the Deputy Directors for OAR and the National Weather Service instructed the directors of PMEL and NDBC to develop a plan for transferring PMEL operations to NDBC. The memo was in response to the Administrator of NOAA's endorsement of a recommendation by the NOAA Program Review Team that TAO mooring operations be consolidated with those at NDBC. After several iterations, the Deputy Administrator of NOAA formally approved a TAO transition plan.

The TAO Transition is being executed in accordance with the approved TAO Transition Plan of August 31, 2004, and yearly Work Plans. FY 2005 accomplishments focused on establishing the NDBC Tropical Mooring Data Assembly Center (DAC) and for NDBC to become familiar with the TAO cruise deployments. NDBC received over 5000 software modules, containing over 2.5 million lines of code, from PMEL. NDBC implemented these modules in a LINUX based distributed system. The NDBC TAO Enterprise Architecture consisted of five subsystems:

- Real-time Processing Subsystem
- Real-time Data Monitoring Subsystem
- Inventory and Calibration Subsystem
- Delayed-mode Data Processing Subsystem
- Web Data Display and Delivery Subsystem.

Since this effort involved a software transition (conversion and integration) instead of a new development effort, NDBC chose a modified Spiral-Development Approach to implement this project. The following Enterprise Architecture documentation were prepared:

- TAO Software Requirement Specification
- TAO Architecture Specification
- TAO End-to-End Test Plan
- TAO Parallel Testing Plan
- TAO DAC/QC Operating Procedures Manual.

In addition to the technical management aspects of TAO, NDBC provided Project Management of the TAO transition to include numerous schedule details and updates, status briefs, contract management, and coordination between PMEL and NDBC. Specific FY 2005 Action Items from the approved TAO Transition Plan of August 31, 2005, is summarized in the following table:

FY 2005 TAO Transition Plan, Action Items and Status

Transition Activity	**Target**	**Status**
*Complete TAO Inventory	07/30/05	Complete*
Establish billet for NOAA Corps Officer at NDBC	06/30/05	Complete
Maintain present data availability	80%	Met
Establish NDBC TAO Data Assembly Center	11/01/05	On Target
Provide Technology Refreshment Plan	08/31/05	Complete
Prepare FY 06 Work Plan	10/15/05	Complete
Continue TAO asset availability for research	Ongoing	Complete
Provide next generation mooring proposal	09/30/05	Deferred Pending Funding
Conduct semi-annual COSC review	04/27/05	Complete

*Completed "Requirements Definition" for TAO Inventory.

The following Table contains the summary of the four quarterly Transition Metric Reports:

Metric	**1st Qtr**	**2nd Qtr**	**3rd Qtr**	**4th Qtr**
Real-time Data	90%	92%	91%	88%
Number of sites visited	41	15	21	35
Number of CTD profiles logged	147	54	83	123
Kilometers of trackline with usable shipboard ADCP data	30,366 recorded	0 recorded	6536 km	24681 km
Number of drifting buoys and profiling floats deployed	17 drifters, 3 Argo	7 drifters, 10 Argo	14 drifters, 14 Argo	20 drifters, 10 Argo
Number of data files delivered by PMEL	35,339	28,088	27,091	21,458
Number of data files delivered by NDBC	0	0	0	0
Number of web page hits recorded by PMEL	6,603,402	6,644,091	5,745,182	5,078,389
Number of web page hits recorded by NDBC	0	0	0	0
Days at sea logged by PMEL mooring technicians	207	70	140	185
Days at sea logged by NDBC Mooring technicians	0	34	56	66
Total expenditures by PMEL	$644K	$644K	$644K	$644K
Total expenditures by NDBC	$53K	$331K	$163K	$240K
Number of "refreshed" components fielded	0	0	0	0
Number of "refreshed" moorings fielded	0	0	0	0

1. Ocean Reference Stations

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PROJECT SUMMARY

The goal of this project is to maintain long-term surface moorings, known as Ocean Reference Stations (ORS), as part of the integrated ocean observing system. The scientific rationale for these stations is to collect long time series of accurate surface meteorology, air-sea fluxes, and upper ocean variability in regions of key interest to climate studies and to use those data to quantify air-sea exchanges of heat, freshwater, and momentum, to describe upper ocean variability and the local response to atmospheric forcing, to motivate and guide improvement to atmospheric, oceanic, and coupled models, to calibrate and guide improvement to remote sensing products and capabilities, and to provide the essential anchor points for the development of new, basin scale fields of the air-sea fluxes. Model, satellite, and climatological fields of surface meteorology and air-sea fluxes have large errors; high quality, in-situ time series are the essential data needed to improve our understanding of atmosphere-ocean coupling and to build more accurate global fields of air-sea fluxes. The in-situ, time series from the ORS are the best way to quantify and monitor the exchange of heat, freshwater and momentum between the ocean and atmosphere at the wide range to time scales that impact climate variability.

Under this effort three sites are being maintained: The “Stratus” site at 20°S, 85°W under the stratus cloud deck off northern Chile (Stratus), the Northwest Tropical Atlantic Station (NTAS) at 15°N, 51°W, and a site north of Hawaii near the Hawaii Ocean Timeseries (HOT) site. The Hawaii ORS was established in July 2004 in cooperation with Dr. Roger Lukas of the University of Hawaii (funded by NSF) and is denoted WHOI-HOTS or WHOTS. After several years of support for mooring deployment and annual servicing under NOAA OGP, the Stratus and NTAS sites have transitioned to long-term Ocean Reference Stations. The Hawaii station is being done in collaboration with investigators that have made shipboard and moored observations in the HOTS region in recent years.

Four principal tasks are identified as a part of the Ocean Reference Stations project: Task I is engineering, oversight, and data management, Task II is maintenance of the Stratus site, Task III is maintenance of the NTAS site, and Task IV is maintenance of the WHOTS site. Progress on each of the Tasks is reported in more detail below. The locations of the Stratus, NTAS, and WHOTS sites are shown in Figure 1.

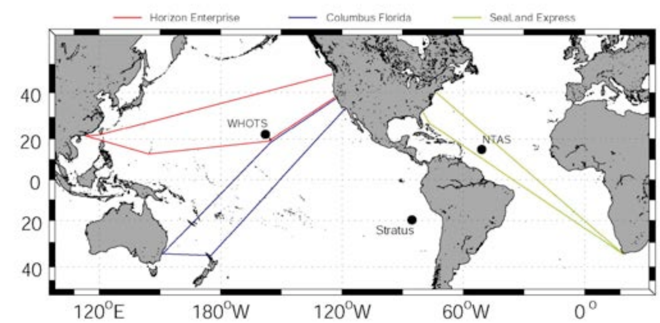

Figure 1. Locations of the three Ocean Reference Stations: Stratus (begun in October 2000), NTAS (begun in March 2001), and WHOTS (begun in July 2004). Schematic routes for Volunteer Observing Ships in the North Pacific, South Pacific and Atlantic are also shown.

Addressing NOAA’s Program Plan

This program directly addresses the sixth element of the Program Plan for Building a Sustained Ocean Observing System for Climate – Ocean Reference Stations. It works in synergy with many of the other elements (Global Surface Drifting Buoy Network, Global Ships of Opportunity, Argo Profiling Float Array, Satellites for Sea Surface Temperature, Sea Surface Height, and Surface Vector Winds) by providing high temporal resolution at fixed points to complement the Lagrangian or spatial sampling of the other elements. It is also an important element of assimilation efforts, as surface fluxes can be diagnosed from the ocean and provide a means to assess the models being used for assimilation.

Management in Cooperation with International Panels

The Ocean Reference Stations project is managed in cooperation with the International Time Series Science Team (co-chaired by R. Weller), a joint planning effort that involves the climate, carbon, and other disciplinary communities interested in long time series and that reports to the Ocean Observations Panel for Climate (OOPC) and to the Partnership for Ocean Global Observations (POGO, an international consortium of directors of oceanographic institutions). The international time series effort is known as OceanSITES (http://www.oceansites.org/OceanSITES). OceanSITES this year became an action group of the JCOMM observations panel. There is also a link to JCOMM observations through the OOPC. The ORS project, and more generally the International Time Series Science Team, because of its importance to and emphasis on air-sea fluxes, has also reported to the WCRP Working Group on Numerical Experimentation (WGNE) to develop explicit links to the weather and climate modeling centers. Through OOPC and WGNE, efforts are underway to make the ORS data available for comparison with weather and climate models. We are now participating in a new WCRP/CLIVAR oversight group on air-sea fluxes formed recently with Chris Fairall as the Chair. We have participated in planning for CLIVAR, for the Carbon Cycle Science Plan implementation, and for SOLAS, working to see that the Ocean Reference Sites develop to serve the needs of the research programs.

Responsible Institution

The Woods Hole Oceanographic Institution is the responsible institution for all aspects of this project.

Interagency and International Partnerships

Planning and implementation of the ORS includes a number of partnerships. The Hawaii site was equipped with ocean instrumentation through a National Science Foundation grant to Roger Lukas of the University of Hawaii. The Stratus site was chosen in collaboration with the Chilean Navy Hydrographic and Oceanographic Service (SHOA), and trips to the Stratus site have involved Chilean (SHOA, the University of Concepcion, and the University of Chile, Santiago) and Ecuadorian (Navy oceanographic office, INOCAR) participation. The Stratus site provided the focal point for the stratus component of the multi-agency cooperative EPIC 2001 field program and is included as a focal point for a CLIVAR VOCALS (VAMOS Ocean Cloud Atmosphere Land Study) process study in 2007. Plueddemann maintains a dialog with IFM Kiel, who maintain transport monitoring moorings near NTAS and would also be the point of contact for NDBC, who has plans for additional surface buoys to be used for improving hurricane predictions in the vicinity of NTAS, and PIRATA. Surface meteorological and air-sea flux data from our sites are made available to various national/international centers (NCEP in the U.S., ECMWF in Europe). There is strong synergy between our program and the National Science Foundation program on Ocean Observatories, and the NSF effort is looked to as the means to develop observatory hardware capable of extending the ORS to higher latitude sites of high scientific and operational climate interest.

Websites:

WHOI website:	http://www.whoi.edu
UOP Group site:	http://uop.whoi.edu
Stratus Project site:	http://uop.whoi.edu/projects/Stratus
NTAS Project site:	http://uop.whoi.edu/projects/NTAS
WHOTS Project site:	http://uop.whoi.edu/projects/WHOTS

FY 2005 PROGRESS

A description of FY 2005 progress is presented in detail below for each of the four ORS tasks. The location of each site and a geographic map was included above in the overview. Note that deployment of the WHOTS ORS in August 2004 represented a two-year acceleration relative to our initial proposal and budget. The additional cost of this work was handled through a Project Acceleration or "Add Task" to the FY2004 and FY2005 ORS budgets. Performance Statistics, Measurements and Data, Logistics, Analysis and Research Results, and Community Service are described as appropriate under the individual Tasks below.

Task I Engineering, Oversight and Data Management

Design of a new buoy for use at the Ocean Reference Stations was completed in FY2003, and the first complete buoy system was deployed in 2004. As of 2005 we have now replaced the old 3-m discus buoy at all three ORS sites with the new, modular foam buoy hulls. The discus buoys were 15-20 year old hulls, which were degrading (corrosion of the welded aluminum) and expensive to ship as they do not fit inside a sea container. The first of the new buoy hulls, tower tops, and cabling systems was utilized for the WHOTS project, deployed in August 2004. The second system was deployed at the Stratus site in December 2004. The third buoy system was deployed at the NTAS site in March 2005.

Performance Statistics

As in FY2004, three ORS are being supported by this oversight task, each requiring a recovery/re-deployment cruise. Data return statistics are presented separately for each site under Tasks II – IV.

Measurements and Data

The oversight task coordinates the common data tasks for the three sites. Oceanographic (velocity, temperature, salinity) and surface meteorological data (wind speed and direction, air and sea surface temperature, rain, incoming shortwave and longwave, relative humidity, and barometric pressure) are processed and stored on disks attached to our workstations. Data acquisition and processing for all three sites continues on schedule. Telemetered data are made available via an FTP server and a website with download capability (http://uop.whoi.edu). We also maintain a public access archive of Upper Ocean Processes Group data from mooring deployments.

Logistics

No significant issues under Task I.

Analysis and Research Highlights

Six new buoys have been built since initiation of the project and are now in use at the three ORS. The flotation element for the new buoy is a 2.7-meter diameter Surlyn foam hull. The two-layer foam buoy is "sandwiched" between aluminum top and bottom plates, and held together with eight 3/4" tie rods. The modular buoy design can be disassembled into components that will fit into a standard ISO container for shipment. A subassembly comprising the water tight electronics well and aluminum instrument tower can be removed from the foam hull for ease of outfitting and testing of instrumentation. Two data loggers and batteries sufficient to power the loggers and tower sensors for one year fit into the instrument well. The meteorological sensor modules are attached to the upper section of the two-part aluminum tower at a height of about 3 m above the water line. The buoy also supports two independent Argos satellite transmission systems that provide near real-time data and continuous monitoring of buoy position.

Work under the oversight task also includes efforts to improve antifouling paints used on ORS and moored instrumentation. We have collaborated on this with Alex Walsh of E-Paint to test new, more user and environment friendly products and are working on documenting the results. We believe we have achieved significant improvement but also find that paint performance is site specific.

A new Iridum-based data communication system was developed and deployed for testing in 2005 at the WHOTS site in parallel with the existing Service Argos data telemetry hardware.

Task II Stratus Site

The stratus surface mooring was originally deployed under a previous grant (from the Pan American Climate Studies) in October 2000. It has been annually redeployed and recovered since that time. During the deployments, hourly-averaged surface meteorology was available from the buoy in near real time via Service ARGOS and a WHOI ftp site. Data exchanges were made with ECMWF, NCEP and others to examine numerical weather prediction model performance and examine air-sea fluxes under the stratus clouds. The telemetered meteorological data are also available from the project website (http://uop.whoi.edu/projects/Stratus). Internally recorded 1-minute meteorological data as well as the oceanographic data, which are only internally recorded, were downloaded from the recovered instrumentation. Data recovery was good, post-calibrations are being done, and data files have been shared with colleagues. Preliminary cruise reports are filed with the State Department soon after the cruise; final documentation that goes to foreign observers and the State Department includes copies of the underway data and a final cruise report (Colbo et al., 2005). Telemetry from the buoy presently deployed indicates that it is on station and both meteorological systems are functioning well with the exception of one RH/AT module.

Work this year included deploying the new and recovering the old mooring, doing calibrations (both pre and post-deployment), data processing, writing cruise reports, preparing mooring hardware and instrumentation for the new deployment and cleaning and assessing the recovered equipment. The FY2005 deployment was carried out aboard the R/V Ronald H. Brown, which sailed from Arica, Chile on December 5, 2004 and arrived into Valparaiso, Chile on December 24, 2004.

The planning and observational preparation for the cruise began many months before the deployment. During the spring of 2004 instruments were gathered and placed on the new mooring buoy for testing. This testing of the instrumentation while mounted on the buoy, and exposed outdoors, was important for the proper gauging of accuracy and reliability. This on¬going burn-in period typically lasts three or more months. In September of 2004, members of the UOP group loaded the R/V Ron Brown in Charleston, with some additional loading a month later in Miami.

The Stratus 4 mooring was recovered on December 11th with no undue problems. The old mooring is traditionally recovered first so as to assess any problems that may have arisen, and to hence make last minute changes on the new mooring. Unlike the previous year where certain upper ocean instruments were fouled by fishing line, no obvious damage to the mooring instrumentation was visible. Biofouling was also reduced this year, whether as a result of new antifoulant paints or ocean conditions is unclear. The Stratus 5 mooring was deployed on December 13, 2004.

Performance Statistics

Data return from the Stratus 4 mooring was 100% of the desired surface meteorological data collected. Data return for subsurface temperature was 94%, for subsurface salinity was 99%, and for ocean currents was 81%. These rates are comparable to those of last year.

Measurements and Data

On the buoy we measure air temperature, sea surface temperature, relative humidity, incoming shortwave and longwave radiation, wind speed and direction, rain rate, and barometric pressure. On the mooring line the instrumentation is concentrated in the upper 300m and measures temperature, salinity, and velocity. During the deployment, high data rate (up to 1 sample per minute) data are stored in each instrument. The internally recorded data go through processing, have calibration information applied, and are subject to preliminary analyses before being made publicly available on our website. In the interim, preliminary versions are made available upon request.

Hourly surface meteorological data are archived at WHOI, arriving within hours of when it was observed. These data are exchanged in near real time with ECMWF and NCEP; they in turn provide operational data at the grid point nearest the model. It is also shared with the Chilean Navy (SHOA). The telemetered meteorological data are also available via the website maintained for this site (http://uop.whoi.edu/stratus). The same data are shared with CLIVAR investigators, especially modelers interested in the Stratus region, with VAMOS investigators in the U.S. and in South America. It is also sent to Peter Glecker at PCMDI for use in the SURFA project. The meteorological data are used to assess the realism of operational atmospheric models in the stratus region. Once per minute as well as hourly surface meteorological time series are provided to the EPIC and VAMOS EPIC investigator communities (including Sandra Yuter, Chris Bretherton, Meghan Cronin) after recovery. The surface meteorological data have been made available to the satellite community (including radiation – Langley, winds – Remote Sensing Systems and JPL, SST – Dick Reynolds, all variables – the SEAFLUX project). The oceanographic data are being used by Weller and a Postdoctoral Investigator (Keir Colbo) at WHOI to investigate air-sea coupling and upper ocean variability under the stratus deck. In parallel it will be compared with ocean model results (with Ragu Murtugudde, Univ. of Maryland and Markus Jochum, NCAR). The initial archive is maintained by the Upper Ocean Processes Group at WHOI, which runs a public access server for their mooring data. We are working with the International Time Series Science Team to develop a number of sites that will maintain as many records of time series stations as can be collected to facilitate access to such data.

Both before the recovery of the old buoy and after the deployment of the new buoy, in situ comparisons of the ship's and buoys' twin meteorological sensors were carried out. These comparisons have been a crucial component of the post-recovery data processing, particularly for sensitive instruments which may suffer damage during the return shipment to WHOI. Extensive shipboard meteorological and air-sea flux instrumentation was installed on the Ron Brown and operated by Chris Fairall and Dan Wolfe from the NOAA Environmental Technology Laboratory in Boulder, CO. The air-sea flux system consists of a fast turbulence system with ship motion corrections, a mean T/RH sensor, solar and IR radiometers, a near surface sea surface temperature sensor, a Particle Measurement Systems (PMS) Lasair-II aerosol spectrometer, and an optical rain gauge.

ETL also operated three remote systems: a Vaisala CT-25K cloud base ceilometer, a 35 GHz vertically pointed Doppler cloud radar, and a 20.6 -31.65 GHz microwave radiometer. ETL has an integrated system in a seatainer that includes a Doppler Ka-band cloud radar and a microwave radiometer. The system can be used to deduce profiles of cloud droplet size, number concentration, liquid water concentration etc. in stratus clouds. If drizzle (i.e., droplets of radius greater than about 50 µm) is present in significant amounts, then the microphysical properties of the drizzle can be obtained from the first three moments of the Doppler spectrum. The radar is extremely sensitive and can detect most tropical cirrus and fair weather cumulus clouds. The Doppler capability can also be used to measure in-cloud vertical velocity statistics.

Marine aerosol concentrations and the processes that produce and remove the aerosols in the southeast Pacific have rarely been studied. Building on last year's results, the Texas A&M University (TAMU) Aerosol Research Group returned to the ship with two instruments to study a large spectrum of aerosol diameters from 12-nm to 15-µm. A Tandem Differential Mobility Analyzer (TDMA) investigated aerosols diameters up to 800-nm, while an Aerodynamic Particle Sizer (APS) model 3321 produced by TSI looked at the remaining aerosols up to 15-µm. The data collected will allow for a better understanding of the marine aerosol's chemical composition and distribution in this region of the world.

The Stratus cruises serve the wider scientific community by providing a platform on which to study the regional ocean. Additional researchers who participated in collaborative research or benefited from shared ship time in FY2005 have come from many institutions: NOAA Environmental Technology Laboratory, Servicio Hydrografico y Oceanografico de la Armada (Chile), University of Concepcion (Chile), Texas A&M University, University of Chile, CSIRO (Australia), and University of Miami.

These collaborations have included: enhanced regional surface flux and lower atmosphere surveys, both offshore and within Chilean coastal waters (NOAA ETL, CSIRO, U. Miami, U. Chile), extensive hydrographic surveys with CTDs and XBTs (multi-user), water sampling in support of biological monitoring (U. Concepcion), regional aerosol surveys of the atmospheric boundary layer (Texas A&M), and the deployment of a tsunami warning buoy (Chilean Navy).

To further support ground-truthing of satellite data and increased understanding of the ocean in the eastern South Pacific, 15 drogue surface drifters and 8 profiling ARGO floats were deployed in the South Pacific along the cruise track.

Logistics

The major logistics concern for the Stratus ORS continues to be the challenge of scheduling ship time. In FY 2005, we were at one point listed on both UNOLS and NOAA ship schedules. This reflects the need for continuing dialog between NOAA and UNOLS about the availability and scheduling of the Class-1 research vessels needed to service the ORS in remote locations such as off Chile.

Analysis and Research Highlights

In the first year of this project, an analysis of the mooring data, together with satellite data, drifter data and climatologies lead to a hypothesis that coastally-generated mesoscale eddies play an important role in the offshore heat and salt budgets. The second year has seen this argument refined and further bolstered by more careful analysis. Colbo and Weller (2005a) synthesized the mooring data with historical hydrographic and satellite data to show that the upper ocean heat and salt budgets had a large component that was contributed by the divergence of the eddy flux. This large transport of cool, fresh water from the coastal upwelling region to the deep ocean through the eddy field has not been noted before. It also might explain the deficiencies observed in many global models of the region, which are not eddy resolving, and hence cannot adequately capture this important oceanic transport. The initial argument has been refined through both the journal review process and, more importantly, feedback from audience members at seminars. In addition, the fourth year of mooring and satellite data has been used to further reduce the statistical uncertainties.

In using the ocean reference station data for this project, as well as others, it was necessary to understand the accuracy of the basic surface meteorology and the derived flux products. To this end a series of meetings was organized for the scientific and engineering staff at WHOI with direct experience of the IMET package. (The IMET package is the standard meteorological sensor suite used on all the Ocean Reference Stations, as well as most US Volunteer Observing Ships and Research Vessels.) These meetings have been synthesized into a single document that has now been transformed into a journal article (Colbo and Weller 2005b). It lays out the expected accuracy of all the individual meteorological sensors in detail, and shows how those errors propagate into the heat, freshwater and momentum fluxes. This is a crucial step in validating the observations and is necessary for any future climate studies involving the Ocean Reference Station data.

The accuracy analysis occurred concurrently with a detailed review of the post-calibration and post-deployment correction procedures. As a result, the four years of existing data were reprocessed in a consistent manner and a methodology for future sensor assessment was created. We envisage this as an on-going project with this as a first step. The detailed comparison of the buoy sensors with each other, the shipboard sensors, and the laboratory standards back at WHOI elucidated a number of areas for improvement. This analysis provides confidence in the post-corrected instrument records, and opens up areas for future inquiry. For instance, the air temperature records on the ship were found to suffer from comparatively more erroneous shortwave forcing than on the buoy. Ship vs. buoy comparisons can help to derive an empirical correction for this error.

The first four years of surface meteorological and air-sea flux data is being used to describe and characterize the surface forcing and atmosphere-ocean coupling observed under the stratus cloud deck at a site close to the region of climatological maximum low cloud cover (Weller and Colbo 2005). This site is data sparse, and these buoy data provide the first accurate long time series that can be used to characterize the site. Both model and climatological values are found to differ significantly from the observations. Though the regime is basically a trade wind regime, with very stable wind direction, wind speed at times drops to low enough values to allow strong diurnal warming in sea surface temperature. Strong diurnal variability is also found in other variables, including the incoming longwave radiation. Links between local variability at diurnal and synoptic time scales to regional synoptic variability are being explored. At the same time significant interannual variability and work is underway to examine whether or not this is tied to change in the South Pacific subtropical circulation in the atmosphere and to other causes.

The model deficiencies in this area naturally raise the question: "How do the models close their heat budgets in the southeast Pacific?" To this end an analysis of the NCAR model has begun, in collaboration with Markus Jochum. The standard saved model output does not allow us to answer the question above with any satisfaction. Together, we are quantifying variables to be saved from future model runs so that the model details can be studied and compared with the observation-based hypothesis.

Another area that is being investigated is the use of satellite data to study these eddy heat fluxes. A major constraint of the satellite data is that it is surface focused, whereas the eddy heat fluxes are concentrated at the thermocline. However, the mooring data can be used to extrapolate surface variables to depth, at least statistically. This kind of analysis would then be used to study spatial variability within the Eastern Subtropical Pacific Ocean and be extended to other eastern subtropical regions.

The Stratus observations and analysis also serve as a starting point for future research. The VAMOS Ocean Climate Atmosphere Land Study (VOCALS) is proposing an interdisciplinary project centered on the Stratus buoy. Colbo, Weller and Breck Owens have proposed a glider study of the eddies as they drift offshore.

Task III NTAS Site

The NTAS project was conceived in order to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong SST anomalies and the likelihood of significant local air-sea interaction on seasonal to decadal time scales. The strategy is to maintain a meteorological measurement station at approximately 15o N, 51o W through successive (annual) turnarounds of a surface mooring. Redundant meteorological systems measure the variables necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas.

NTAS has two primary science objectives: (1) Determine the air-sea fluxes of heat, moisture and momentum in the northwest tropical Atlantic using high-quality, in-situ meteorological measurements from a moored buoy. (2) Compare the in-situ fluxes to those available from operational models and satellites, identify the flux components with the largest discrepancies, and investigate the reasons for the discrepancies. An ancillary objective is to compute the local (one-dimensional) oceanic budgets of heat and momentum and determine the degree to which these budgets are locally balanced.

A mooring turn-around cruise was conducted on the NOAA ship Ronald H. Brown in order to retrieve the existing mooring (NTAS-4, deployed 21 February 2004) and replace it with a new mooring (NTAS-5). In preparation for this cruise, three Air-Sea Interaction Meteorology (ASIMET) systems were assembled and tested. Two systems, comprised of the best performing sensors, were mounted on the newly developed 2.7 m modular ORS buoy in preparation for deployment. The NTAS-5 mooring was deployed on 11 March 2005 and the NTAS-4 mooring was recovered on 13 March. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. To ensure high-quality meteorological data, all NTAS-5 sensors were calibrated prior to deployment, and NTAS-4 sensors will be post-calibrated. A cruise report is in preparation.

Performance Statistics

Data return from the meteorological system on NTAS-4 was 100% for all sensors. NTAS-2 and 3 also had 100% data return. NTAS-1 had partial data return (60–90%) from AT, RH, SST and SSC sensors. However, the purposeful redundancy of the system meant that alternate sensors could be used in each case, and a complete record of NTAS-1 surface meteorology was obtained.

Measurements and Data

Redundant meteorological systems on the surface buoy measure the variables (wind speed and direction, air and sea surface temperature, incoming shortwave and longwave radiation, relative humidity, barometric pressure, precipitation) necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas and also sea surface salinity.

Preliminary processing of the NTAS-4 meteorological data has been completed. The comparison period showed very encouraging results, indicating little degradation of NTAS-4 sensor performance after one year at sea. After post-calibration of the sensors, the corrected, 1¬min data will be used for further analyses. The uncorrected, hourly Argos data from NTAS-4 are available on-line from the Upper Ocean Processes (UOP) group web site (http://uop.whoi.edu/projects/NTAS). At present, about 7 months of hourly meteorological data from NTAS-5 are also available for examination on the UOP web site. Preliminary evaluation indicates that all NTAS-5 sensors are performing as expected with the exception of one wind module that failed in September 2005.

Meteorological sensors from NTAS-1, 2 and 3 have been post-calibrated, and NTAS-1 and 2 data have been post-processed. Hourly averaged files from the resulting data sets have been posted on the UOP web page. The 1 min data are being used as the basis for air-sea flux computations using bulk formulas.

Logistics

The NTAS project used 14 days of ship time on the Ronald H. Brown in FY2005. Logistical challenges and unanticipated project costs tend to revolve around ports, shipping and cruise duration. For example, in 2002 the mooring service cruise was a very efficient 7-day round-trip out of Barbados, but we incurred substantial costs for port services and shipping relative to our budget, which was for a domestic port. For the 2003 cruise, shipping costs were reduced substantially because we were able to partially load and offload Oceanus in Woods Hole. However, the cruise duration (Barbados/Woods Hole rather than Barbados/Barbados) was many days longer than budgeted, and we effectively traded shipping costs for salary costs. In 2005 the situation was intermediate between these two extremes. The cruise was on the Ronald H. Brown out of Barbados, so the outbound shipping costs were relatively high. This was mitigated by the fact that some equipment from the Stratus deployment was able to be stored on the Brown for use by NTAS, and by the fact that the return shipment was from a domestic port (Charleston, South Carolina). However, salaries for the cruise (14 days, Barbados/Charleston) were higher than budgeted.

Analysis and Research Highlights

Observations of the annual cycle at the NTAS site indicate that spring (MAM) is characterized by SST increasing from its annual minimum and very low levels of precipitation. Summer (JJA) is characterized by steady northeast winds (towards 255°) at 6-8 m/s and continuing increases in SST. Episodic precipitation begins in late summer. Fall (SON) is characterized by reduced solar radiation, SST decreasing from its annual maximum, persistent precipitation, and variable winds. By mid winter (DFJ), solar radiation begins to increase, precipitation decreases, and winds become steadier. A distinct surface salinity minimum is observed in early winter some years. Monthly averages show a clear tendency for strong precipitation to be associated with SST above 27°C, as is characteristic of the Inter-Tropical Convergence Zone.

The net heat flux observed at the NTAS ORS reaches a maximum of about 100 in August and a minimum of about -50 in January (Fig. 2, left). The largest contribution is from shortwave radiation, which is offset by latent heat losses. Longwave losses are significant in the annual mean, but contribute little to the seasonal cycle. Sensible losses are small, effectively negligible relative to the other terms.

Fluxes from the NTAS ORS were compared to numerical model products from ECMWF and NCEP, as well as to climatology for the region (Fig. 2, right). The ORS data were from the best performing sensors on the buoy, logged at 1 min intervals, with fluxes computed using the TOGA COARE bulk flux algorithm. The ECMWF data were from the surface meteorology and diagnostics variables of the operational forecast model for the grid point nearest the buoy (courtesy of Anton Beljaars). NCEP-1 fluxes were from the NCEP/NCAR Reanalysis-1 data set and the NCEP-2 fluxes were from the NCEP/DOE

Reanalysis-2 data set. The SOC climatology is based on COADS ship reports from 1980-1993. The ASIMET (1 min) and ECMWF (1 hour) data were averaged over six hours to match the NCEP time base. Note that the net heat flux for all of the model products is biased low, and that the timing zero-crossings differ by 1-2 months. The SOC climatology is a better match to the annual cycle than any of the models. The situation is different for wind stress, where the model products compare well with the observed flux, and are clearly better than the climatology.

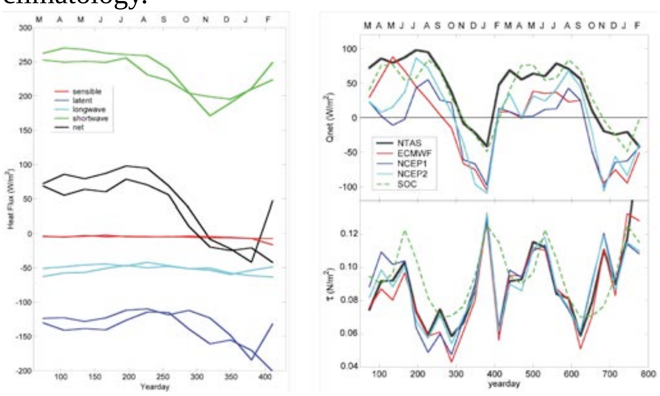

Figure 2. The annual cycle of heat and momentum flux at NTAS. The contribution of heat flux components to the net heat flux is shown for two years of ORS data (right). Two years of net heat flux and momentum flux from the ORS are compared with model products and the SOC climatology (left).

The two-year mean net heat flux is significantly underestimated by the three models (mean differences are 4-5 times larger than the expected error of about 10 W/m2 from the buoy data). For ECMWF and NCEP-1 this is due to overestimation of latent heat losses and underestimation of shortwave gains. NCEP-2 shows a dramatic improvement in shortwave flux relative to NCEP-1, but still has a large net heat flux error due to substantial overestimation of latent heat losses. In addition, all three models indicate a negative two-year mean net heat flux, whereas the observed value is +40 W/m2.

Task IV Hawaii Site

This past year, we completed the first year of deployment at this new ORS, called WHOTS, which is located at the Hawaii Ocean Time-series site. The Hawaii Ocean Time-series (HOT) site, 100 km north of Oahu, Hawaii, has been occupied since 1988 as a part of the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). Among the HOT science goals are to document and understand seasonal and interannual variability of water masses, relate water mass variations to gyre fluctuations, and develop a climatology of high-frequency physical variability in the context of interdisciplinary time series studies. The primary intent of the WHOI Hawaii Ocean Timeseries Station (WHOTS) mooring is to provide long-term, high-quality air-sea fluxes as a coordinated part of the HOT program and contribute to the goals of observing heat, fresh water and chemical fluxes at a site representative of the oligotrophic North Pacific Ocean. It is expected that establishment of the WHOTS mooring will accelerate progress toward understanding multidisciplinary science at the site, provide an anchor site for developing air-sea flux fields in the Pacific, and provide a new regime in which to examine atmospheric, oceanic, and coupled model performance as well as the performance of remote sensing methods. The deployment of the ORS mooring at the HOT site in August 2004 represented a two year advancement of the timetable originally proposed (financial support for this acceleration was provided by the NOAA Office of Climate Observations as an Add Task).

Performance Statistics

Data return from the meteorological instrumentation on WHOTS-1 was 100% for all measurements except wind speed and direction. One wind sensor failed after about 5 months on station. Due to the redundancy of the system, a complete record of surface meteorology was obtained.

Measurements and Data

The observational strategy is to maintain a surface mooring at approximately 22.75° N, 158° W, instrumented to obtain meteorological and upper ocean measurements, through successive (annual) turnarounds done in cooperation with HOT investigators. Redundant meteorological systems on the surface buoy measure the variables (wind speed and direction, air and sea surface temperature, incoming shortwave and longwave radiation, relative humidity, barometric pressure, precipitation) necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas and also sea surface salinity. Subsurface oceanographic sensors on the mooring are being provided by Roger Lukas (U. Hawaii; funded by the National Science Foundation).

A mooring turn-around cruise was conducted in 2005 on the Scripps ship Melville in order to retrieve the existing mooring (WHOTS-1, deployed August 2004) and replace it with the new mooring (WHOTS-2). In preparation for this cruise, three Air-Sea Interaction Meteorology (ASIMET) systems were assembled and tested. Two systems, comprised of the best performing sensors, were mounted on a 2.7 m modular ORS buoy in preparation for deployment. The WHOTS-1 mooring was recovered on 26 July 2005 and the WHOTS-2 mooring was deployed on 28 July. Periods of about 24 hours prior to the WHOTS-1 recovery and after the WHOTS-2 deployment were dedicated to an intercomparison of the buoy and shipboard meteorological systems. The WHOTS-2 mooring was used as a test-bed for implementation of an Iridium data telemetry system, developed under the ORS Engineering, Oversight and Data project. Initial results indicate that the system is working, providing a data stream that is redundant with the standard Argos telemetry. To ensure high-quality meteorological data, all WHOTS-2 sensors were calibrated prior to deployment, and WHOTS-1 sensors will be post-calibrated.

Preliminary processing of the WHOTS-1 meteorological data has been completed. Data return was very good, with all sensors operating for the complete deployment period except one wind sensor which failed after about 5 months. The intercomparison period showed encouraging results, but did indicate that some sensor positions on the 2.7 m buoy tower may be suboptimal. The uncorrected, hourly Argos data from WHOTS-1, and the first few weeks of data from WHOTS-2, are available on-line from the Upper Ocean Processes (UOP) group web site (http://uop.whoi.edu/projects/WHOTS).

Logistics

The WHOTS mooring is nearby the Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks (MOSEAN) mooring of Tommy Dickey (U.C. Santa Barbara; funded by the National Oceanographic Partnership Program). We have established links with U. Hawaii and the MOSEAN group to improve the efficiency of field logistics.

Analysis and Research Highlights

The data from the first are just now going through initial post-processing, including application of post-deployment calibrations and quality control. After post-calibration of the sensors, the corrected, 1-min data will be used for further analyses. A cruise report is in preparation.

Of particular interest in the analysis effort will be coordinating with the investigators of the NOPP-funded biogeochemical mooring, with the HOTS ship sampling, and with Dr. Charlie Eriksen (U. Washington) who deployed a glider that navigated a “x”-shaped pattern spanning both moorings to look at eddies with strong ocean color and nutrient signatures that propagated through site. Additional sampling of such an eddy by HOTS investigators was supported by the WHOTS cruise in August 2005.

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2. Western Boundary Time Series in the Atlantic Ocean

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PROJECT SUMMARY

In the subtropical North Atlantic, the meridional overturning circulation consists primarily of two western boundary components: the northward flowing Gulf Stream and the southward flowing Deep Western Boundary Current. The Gulf Stream is the strong surface intensified flow along the east coast of the United States that brings warms waters of tropical origin along the eastern seaboard of the United States. The Gulf Stream also brings with it carbon, nutrients and tropical fish. It supplies warm waters along the coast that impact a multitude of important climate phenomena including hurricane intensification, winter storm formation and moderate European weather. The Gulf Stream includes the bulk of what we call the upper limb of the thermohaline overturning circulation in the subtropical Atlantic, in addition to a strong wind-driven flow. As the Gulf Stream flows northward, it loses heat to the atmosphere until eventually in the subpolar North Atlantic some of it becomes cold enough to sink to the bottom of the ocean. This cold deep water then returns southward along the continental slope of the eastern United States as the Deep Western Boundary Current.

Along the east coast of Florida, the Gulf Stream is often referred to as the Florida Current and is fortuitously confined within the limited geographic channel between Florida and the Bahamas Islands, thus making a long-term observing system both cost effective and sustainable. Similarly, the Deep Western Boundary Current is located within several hundred miles to the east of the Abaco Island, Grand Bahamas. The convenient geometry of the Bahamas Island chain thus allows an effective choke point for establishing a long term monitoring program of this deep limb of the overturning circulation.

This project consists of two components to monitor the western boundary currents in the subtropical Atlantic: Task 1: Real-time Florida Current transport measurements using a submarine telephone cable plus calibration cruises, Task 2: Deep Western Boundary Current water property measurements using dedicated research ship time and quasi-real-time transport monitoring using moored instruments.

Project Description

The main objective of this project is to observe and monitor the western boundary currents at mid latitudes in the North Atlantic. The project has two main observational components (Figure 1): the continuous measurement of the Florida current and the Deep Western Boundary Current.

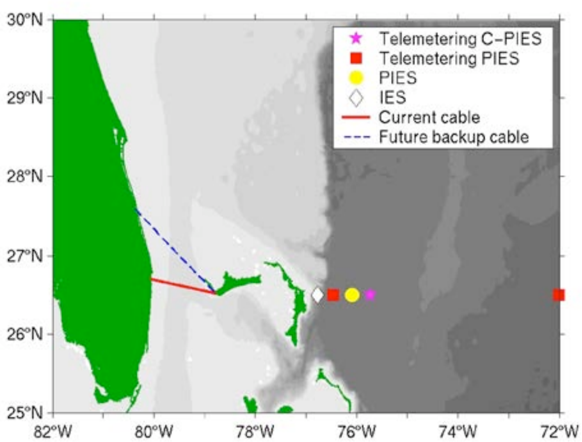

Figure 1: Observational components of the western boundary currents time series in the North Atlantic. CTD profiles are obtained once a year along the IES mooring line out to at least 72ºW.

Task 1: Continuous Transport measurements of the Florida Current

The project maintains NOAA's well-established and climatically significant Florida Current volume transport time series. Over 20 years of daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-use cables spanning the Straits of Florida. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory. These transport measurements contain decadal changes on the order of 10-25% of the long-term mean transport and these decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation, and by extension with the large-scale sea-surface temperature patterns associated with the North Atlantic Oscillation, suggests connections to tropical Atlantic variability on climatically significant time scales. These strong correlations also link the Florida Current transport with the numerous significant weather and climate phenomena that are thought to be related through large scale ocean-atmosphere patterns in the Atlantic, including decadal and inter-decadal variations in fisheries, rainfall, and hurricane activity.

Funding provides for continuous collection of cable voltages (every minute) and automated processing of simple geomagnetic corrections. In addition to the cable measurements, quarterly calibration cruises are required for this project's success. These measurements complement a related project that measures the upper ocean thermal structure in the Atlantic through high-density VOS XBT observations. Funding provides for four two-day small charter boat calibration cruises on the R/V F. G. WALTON SMITH each year.

Task 2: Deep Western Boundary Current Time Series

Over the past 20 years a variety of snapshot sections and time series moorings have been placed along the continental slope east of Abaco Island, Grand Bahamas, in order to monitor variability of the transport carried by the Deep Western Boundary Current. The Abaco time series began in August 1984 when the NOAA Subtropical Atlantic Climate Studies Program extended its Straits of Florida program to include measurements of western boundary current transports and water mass properties east of Abaco Island, Grand Bahamas. Since 1986, over 20 hydrographic sections have been completed east of Abaco, most including direct velocity observations, and salinity and oxygen bottle samples. Many sections have also included carbon, chloroflourocarbon, and other tracers.

The repeated hydrographic and tracer sampling at Abaco has established a high-resolution, high quality record of water mass properties in the Deep Western Boundary Current at 26ºN. Events such as the intense convection period in the Labrador Sea and the renewal of classical Labrador Sea Water in the 1980's are clearly reflected in the cooling and freshening of the Deep Western Boundary Current waters off Abaco, and the arrival of a strong chlorofluorocarbon pulse approximately 10 years later. This data set is unique in that it is not a single time series site but in instead a time series of transport sections, including high quality water property measurements, of which very few are available in the ocean that approach even onedecade in length.

This task includes annual cruises across the DWBC to measure the water mass properties and transports and beginning in September 2004 a new low-cost monitoring system was put in place to provide continuous long-term monitoring of this flow in quasi-real-time. This new monitoring system includes a moored array Inverted Echo Sounders (IESs), some additionally equipped with bottom pressure gauges (PIES) and bottom current meters (C-PIES), across the shallow northward flowing Antilles Current as well as the southward flowing Deep Western Boundary Current. The IES monitoring system will also be compared to a series of monitoring systems that have been deployed as part of an interagency and international partnership that is testing a variety of low cost methods for observing the complete meridional overturning circulation cell at 26ºN in the Atlantic.

Continued time series observations at Abaco are seen as serving three main purposes for climate variability studies:

- Monitoring of the DWBC for water mass and transport signatures related to changes in the strengths and regions of high latitude water mass formation in the North Atlantic for the ultimate purpose of assessing rapid climate change.
- Serving as a western boundary endpoint of a subtropical meridional overturning circulation (MOC)/heat flux monitoring system designed to measure the interior dynamic height difference across the entire Atlantic basin and its associated baroclinic heat transport.
- Monitoring the intensity of the Antilles Current as an index (together with the Florida Current) of interannual variability in the strength of the subtropical gyre.

Addressing NOAA's Program Plan

The program plan for "Building a Sustained Ocean Observing System for Climate" includes the objectives of:

1. Documenting the heat uptake, transport, and release by the ocean; and
2. Documenting the air-sea exchange of water and the ocean's overturning circulation.

This project is one component of the "Ocean Reference Station" at approximately 26ºN in the Atlantic Ocean that specifically addresses these goals by providing long term integrated measures of the global thermohaline (overturning) circulation. This project is designed to deliver yearly estimates of the state of the thermohaline circulation, i.e. its intensity, properties, and heat transport. Heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Monitoring the transport within the ocean is a central element of documenting the overturning circulation of fresh water, heat and carbon uptake and release. Long-term monitoring of key choke points, such as the boundary currents along the continents including the Gulf Stream and the Deep Western Boundary Current, will provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the bulk of the Meridional Overturning Circulation.

Management in Cooperation with International Panels

This program is managed under the AOML Global Ocean Observing System (GOOS) Center, created in cooperation with national and international steering committees to provide an administrative umbrella that coordinates several operational oceanographic data collection networks. As part of GOOS, this program falls within the Observations Program Area of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM).

Responsible institution

NOAA/AOML is responsible for this project.

Interagency and international partnerships

This project provides the cornerstone observations required for a national and international pilot program to develop an observing system to monitor the intensity and heat transport of the overturning circulation at 26ºN in the Atlantic. Partners in this project include the National Science Foundation, University of Miami, Woods Hole Oceanographic Institution, University of Southampton (England), the United Kingdom's National Environmental Research Council (NERC) and NOAA/AOML. This NOAA project provides the essential Florida Current component of the monitoring system, plus ship time, moored and hydrographic observations to augment the international observations obtained east of Abaco Island, Grand Bahamas. Programs include the NSF sponsored Meridional Overturning, Circulation and Heat transport Array (MOCHA) proposal and the NERC sponsored Rapid Climate Change program.

Project management and the Ten Climate Monitoring Principles

This program is managed in accordance with the Ten Climate Monitoring Principles (Program Plan, Mike Johnson, 2003). This time series contains several gaps in the continuous record due logistical requirements, funding shortfalls and, more recently, to instrument failure. To better assure an adequate climate record, parallel testing and parallel measurements are required to assure continuity of the time series without gaps. 'Data quality and continuity', principle 4 of the ten climate monitoring principles, and 'data and meta data access', principle 10, have suffered as a direct result. We are in the process of designing and building a new monitoring system for a backup cable across the Florida Straits with funds recently provided by OCO. This backup system should assure improved data quality and continuity.

FY 2005 PROGRESS

Instrument/platform acquisitions for fiscal year and where equipment was deployed

Task 1: Continuous transport of the Florida Current

Recording instruments are located at Eight Mile Rock, , Grand Bahamas Island. At Eight Mile Rock and in West Palm Beach, Florida, electrode equipment is in place, securing a stable reference voltage (i.e. grounds) at either end of the submerged telephone cable owned by AT&T. The monitored cable can be seen in Figure 1, stretching across the Florida Straits. Data acquisition has continued without significant incident since October 29, 2004 when a new monitoring system was installed after Hurricane Frances and then Hurricane Jeanne substantially damaged the previous infrastructure at the Bahamas facility including telephone service and electricity. As a result of this dramatic occurrence, some data from the first few weeks of the FY is likely to be unrecoverable. This FY has seen the adoption of a stable system of processing and quality control for both the calibration section data and the cable transport data. Cable voltages are recorded every minute, and are post processed to form daily transport estimate. The location of submerged cable is shown in Figure 1. The Table 1 below shows the number of hourly averaged voltage measurements.

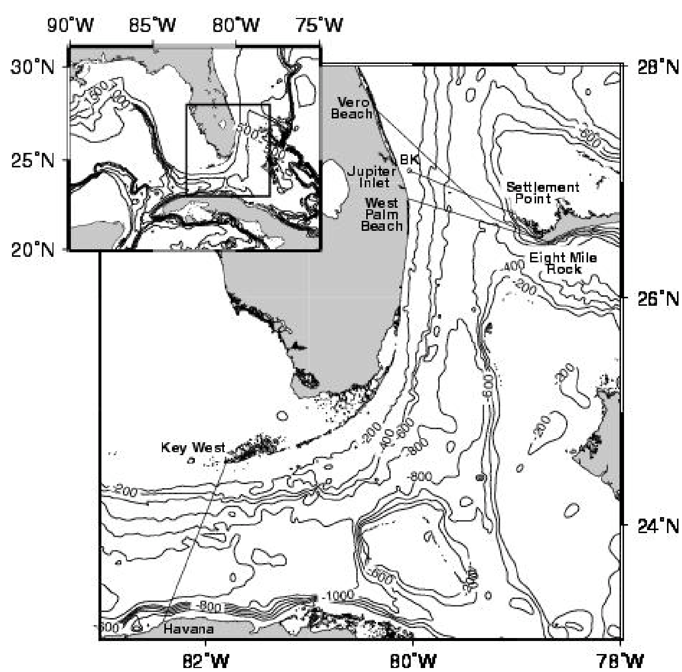

Figure 1: Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises

FY 2005	FY 2004	FY 2003	FY 2002
88% Return[1]	87% Return[1]	89% Return	72% Return[2]

[1]Note a pair of hurricanes destroyed the recording equipment and damaged the infrastructure in Sept. 2004.
[2]Note old recording system failed in FY 2002.

Table 1: Data return from continuous cable voltages (% Return based on the maximum number of days possible in one year: e.g. 365 for non-leap years and 366 for leap years like 2004).

Planned Cruise	FY 2005	FY 2004	FY 2003	FY 2002
1	Nov 19, 2004 dropsonde lost	Dec 9, 2003	clearance problems	weather problems
2	Nov 29, 2004	Dec 16, 2003	clearance problems	Dec 14, 2001
3	Feb 17, 2005	Jan 9, 2004	equipment problems	Mar 12, 2002
4	Feb 24, 2005 section incomplete due to weather	Jan 13, 2004 GPS failure on two stations	Mar 18, 2003	Mar 18, 2002
5	May 18, 2005	May 7, 2004	June 7, 2003 dropsonde failure	June 3, 2002
6	Jun 21, 2005 dropsonde lost	May 24, 2004	no dropsonde	June 6, 2002
7	Aug 31, 2005	Jun 7, 2004	no dropsonde	Aug 23, 2002 dropsonde lost
8		Jun 11, 2004	no dropsonde	
9		Aug 24, 2004		
10		Sep 1, 2004 GPS antenna failure		
	50% successful[3]	80% successful[4]	13% successful[5]	63% successful

[3]Final cruise postponed to next fiscal year due to weather/scheduling issues. Two dropsonde instruments were lost due to equipment malfunctions. One cruise was only partially completed due to weather.
[4]Two additional cruises were planned for FY04 due to dropsonde failures in FY03.
[5]Sections missing due to: dropsonde failure (4) and clearance problems (2).

Table 2: Cruise dates for 1-day small boat calibration cruises using dropsonde instrument.

Small charter boat calibration trips

A total of seven 1-day surveys were conducted using a dropsonde profiler (the final cruise was postponed into the next FY due to weather). Measurements are taken at nine stations (shown in Figure 1) and include vertically averaged horizontal velocity, surface velocity and expendable temperature probes (XBTs). The cruise dates are shown in Table 2.

New equipment was purchased this FY to build new dropsondes after the loss two dropsondes. The new purchases included self-recording conductivity, temperature depth (CTD) recorders, GPS, radio transmitter, glass pressure housing, batteries and antennae

Full Water Column calibration cruises

Two-day cruises on RV Walton Smith are generally scheduled four times per year (the final cruise of FY05 is being postponed into early FY06). All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figure 1. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

FY 2005		FY 2004		FY 2003	
Date	Water Samples	Date	Water Samples	Date	Water Samples
Dec 3-4, 2004	58 O2, 44 S	Jan 8-9, 2003	55 O2, 46 S	Nov 20, 2002	43 O2, 44 S
Jun 3-4, 2005	58 O2, 45 S	May 6-7, 2004	47 O2, 43 S	Mar 22, 2003	59 O2, 49 S
Jul 11-12, 2005	58 O2, 45 S	Jul 4-5, 2004	56 O2, 46 S	Jul 16, 2003	56 O2, 46 S
		Aug 27-28, 2004	55 O2, 42 S	Oct 2-3, 2003	57 O2, 43 S
67% of Planned Cruises[6]		100% of Planned Cruises		100% of Planned Cruises	

[6]The last cruise was postponed to next FY due to weather/equipment/scheduling problems.

Table 3: Cruise dates for 2-day calibration cruises on the R/V Walton Smith.

FY	Date	Stations	Bottle Samples	Comments
2005	Sep, 2005	53	728 O2, 728 S	1 IES deployed, 2 IESs recovered, data from 3 IESs recovered via acoustic telemetry
2005	May, 2005	70	1084 O2, 1180 S	1 IES deployed, data recovered from 3 IESs via acoustic telemetry
2004	Sep, 2004	42	634 O2, 629 S	5 IES mooring deployments
2003	Feb, 2003	54	844 O2, 843 S	3 IES Mooring recoveries, Short Seabeam in Florida Straits
2002	June 2002	57	924 O2, 924 S	Extended Seabeam survey east of Abaco Island, SF6 samples.
2001	April 2001	33	607 O2, 659 S	4 IES mooring deployments

Table 4: Cruise dates and water samples taken for Large Vessel full water column surveys of the Deep Western Boundary Current. May 2005 cruise aboard the R/V Knorr with ship time funded by NSF. April 2001 cruise on the R/V Oceanus. All other cruises were conducted on the R/V Ronald H. Brown.

Task 2: Deep Western Boundary Current time series

Two full water column cruises of CTD, lowered ADCP, profiles were conducted within the Florida Straits and east of Abaco Island, Bahamas, one on the NOAA Ship Ronald H. Brown, and the other on the R/V Knorr. At each station, a package consisting of a Seabird Electronics Model 9/11+ CTD O2 system, an RDI 150 kHz Workhorse Lowered Acoustic Doppler Current Profiler, a RDI 300 kHz Workhorse Lowered Acoustic Doppler Current Profiler, and 24 10-liter Niskin bottles, was lowered to the bottom. This provided profiles of velocity, pressure, salinity (conductivity), temperature, and dissolved oxygen concentration. Water samples were collected at various depths and analyzed for salinity and oxygen concentration to aid with CTD calibration.

The first hydrographic cruise this year took place on the RV Knorr during May 2-26, while the second took place on the NOAA Ship RONALD H. BROWN during Sept 11-24. The stations were occupied at the locations shown in Figure 2. Table 4 lists the cruise dates and bottle samples taken compared to previous years. Five inverted echo sounders (IES) sites were maintained as shown in Figure 2 including: one IES, three IES with pressure sensors (PIES) and one IES with pressure sensor and bottom current meter (C-PIES).

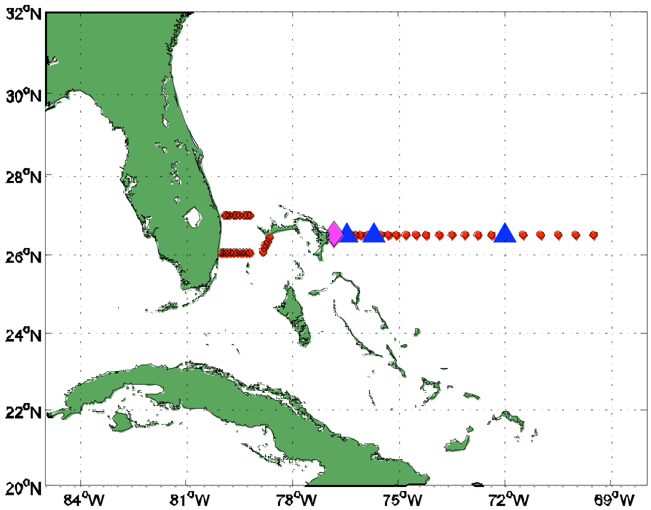

Figure 2: Approximate locations of full water column hydrographic stations sampled on the two cruises in FY 2005. Red circles denote CTD sites. Blue triangles denote PIES moorings and the pink square denotes a C-PIES mooring.

Where data are stored, data distribution, availability and access to data

All data are stored at AOML and are available upon request. Cable data are collected and stored on a computer in the Bahamas and downloaded daily to AOML. Cable data are available via the internet (web site: www.aoml.noaa.gov/floridacurrent/) in near real-time (4-5 day delay). CTD data will be distributed to NODC and the WOCE hydrographic program office when final calibration is complete. Florida Current transport estimates from the small boat observations are also available at the above web address.

How data are currently being used and shared

Small boat calibration data are processed to supply a total transport of the Florida Current and are used to check the cable voltage measurements. Water bottle sample data are used to calibrate CTD data, to compute property fluxes within the Deep Western Boundary Current and Florida Current. Water properties of the Deep Western Boundary Current are used to infer time scales of deep-water renewal and monitor the intensity of the thermohaline circulation. All data are stored at AOML and are freely available upon request.

Anticipated and unanticipated project costs

Task 1, Calibration cruises: Additional unanticipated costs included the loss of the dropsonde equipment that required the replacement of two dropsondes.

Problems encountered

Task 1, Continuous cable voltage recording: Problems include the destruction of the cable recording equipment and the loss of electricity and phone service in the Bahamas after the passage of Hurricanes Frances and Jeanne in late FY04, and the failure of a computer system in August 2005.
Task 1, Calibration cruises: Problems included the loss of two dropsondes and communication problems with one of the newly built dropsondes.
Task 2, DWBC cruise: The broadband 150 kHz lowered ADCP failed on the Sep, 2005 R/V Brown cruise. Velocity data has not historically been part of the funding under this project, but is required for the joint project for the United Kingdom's Rapid Climate Change Project and the National Science Foundation (NSF) Meridional Overturning Circulation and Heat transport Array (MOCHA) Project. Additional costs associated with repairs will be required. The source for these funds is unknown at this time.

Logistical considerations

- Clearances to do technical work in the Bahamas to the recording equipment are necessary and very difficult to obtain. Blanket clearances are desired.
- Blanket clearances are necessary to work on calibration cruises due to the short lead-time for scheduling the cruises.
- Bahamian clearances for the large ship Deep Western Boundary Current cruises are also necessary.
- This work would not be possible without the considerable help of BattelCo, the Bahamian telephone company, for the use of their facilities to store our equipment, install phone lines and to instrument their telephone submerged cable.
- Vigilance towards cable protection activities is also required to prevent the cable from being inadvertently cut.
- Ship days required:

Ship	Seadays per trip	Trips per year	Total Seadays Including weather days
RV Ronald H. Brown	14	1	16
RV Walton Smith	2	5	10
Charter Fishing Boat	1	10	10

Table 5: Ship days required.

Research highlights

1. Numerous climate models have shown that variations in the Meridional Overturning Cell could have significant climate impacts over a wide range of locations around the globe. We compared the use of bottom pressure gauges and inverted echo sounders to a more traditional picket fence of current meters and showed that the far less expensive option of using bottom pressure and inverted echo sounders was able to reproduce the transport fluctuations observed by the current meter arrays well. This will lead to more efficient, lower cost monitoring system (now funded through the NOAA Office of Climate Observations) for the lower limb of the meridional overturning circulation.
2. For the first time, totally independent estimates (viz., indirect observations versus an operational global ocean circulation model) of the Florida Current volume transport are available for cross-validation, not only of monthly means but also of transport events forced by synoptic scale atmospheric forcing. The close comparison between the cable-derived and model transport estimates not only validate the Global operational Navy model (G-NCOM) per se, but also imply that its atmospheric forcing used (from NOGAPS) captures the cold front passages reasonably well. This kind of comparison is vital to the ongoing development of ocean circulation models and observing systems in order to understand and predict climate variability.
3. An international program was recently funded to monitor the strength of the total meridional overturning circulation volume and heat transport at mid- latitudes in the North Atlantic to monitor for rapid climate change signals. Cable voltages measured along a submerged telephone cable across the Florida Current have been newly calibrated to generate a continuous heat transport time series of the Florida Current, which is crucial for trans-basin heat flux estimates. This new calibration will be critical for the international programs success and robust estimates of the net flow of the meridional overturning circulation used to predict climate change

Task 1: Continuous transport of the Florida Current

Voltage estimates recorded from the submarine cable were corrected for geomagnetic variations due to the changing ionosphere and then converted into transports using the section calibration information. Transports are shown in Figure 3 and are available on the project web site.

In order to assure research quality data, these data will need to be carefully examined and corrected by judicious use of the final geomagnetic data, comparing tidal signals, and using tidally-corrected transport calibration data. Unfortunately, electrode failure is to be anticipated (and similar problems have occurred in the past, which were corrected – see Larsen, 1992). In order to assure the best climate time series several steps are recommended:

1. A backup system must be available and in good repair, in case of catastrophic failure of the primary recording system.
2. A second submarine cable should be instrumented and recorded in parallel. This would guard against failure of the submarine cable itself and provide a useful diagnostic for comparison with the primary cable. Funding for this recently became available from OCO, and the new cable systems are being designed and built.

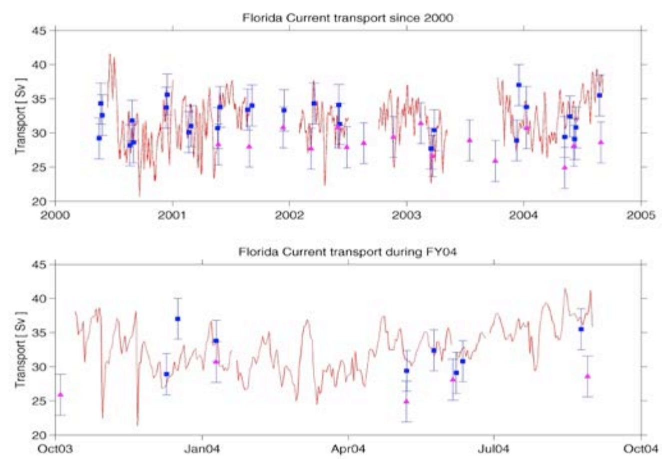

Figure 3: Daily estimates of Florida Current transport determined by voltages induced in submerged, submarine telephone cable. Transports given in Sv (1 Sv = 106 m3 s-1). Symbols with error bars represent calibration cruises from: small charter boats (blue squares) and full water column surveys (red triangles).

Task 1: Florida Current calibration cruises

Calibration cruises show transports of the Florida current varying from 26.9 to 30.8 Sv. Note that, the current is not always monotonically northward. A subsurface southward flow between 150 to 500 meters deep along the western side of the Strait can be seen in several of the full water column sections.

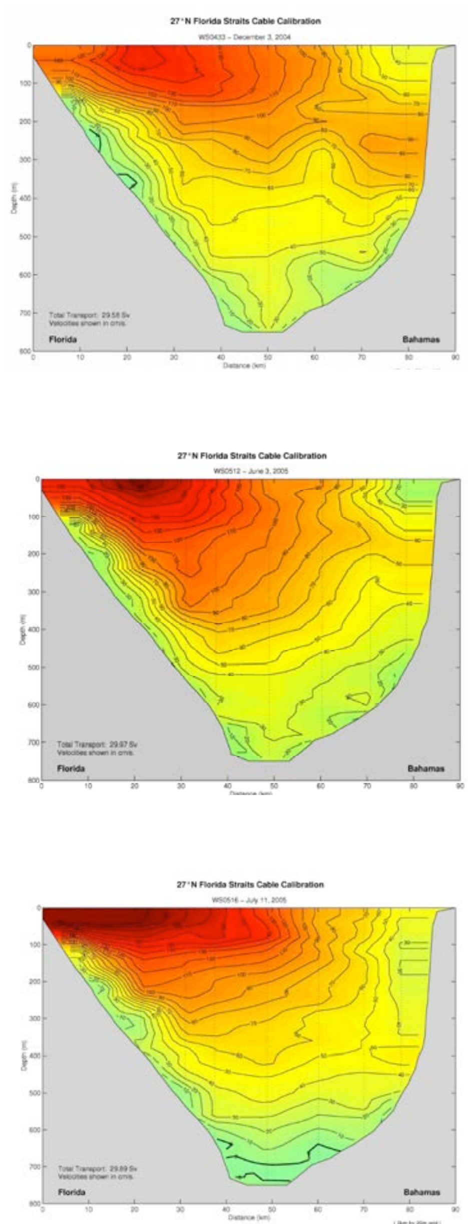

Figure 4: Full water column calibration cruises show the complex vertical structure of the Florida Current. The last cruise has been postponed to next FY.

Task 2: Deep Western Boundary Current Time Series

Full water column Deep Western Boundary Current CTD/LADCP sections show the arrival of newly formed Labrador Sea water in the center of the subtropical gyre beginning in late 1994 (Figure 5). Since its first arrival, the Labrador Sea Water is seen to become progressively colder and fresher and its influence is felt further and further offshore.

In preparation for the inverted echo sounder deployments in FY 2004, a preliminary test of the use of PIES for measuring the variability of the Deep Western Boundary Current and the Antilles Current utilizing three inverted echo sounder records (IES) and two bottom pressure records (BPR) from 1996-1997 was completed. Comparisons are shown between transports estimates derived from the IES and BPR (Figure 6) showing excellent agreement with the more expensive and traditional current meter moorings (Meinen et al 2004).

Figure 5: Potential temperature and Salinity time series within the Deep Western Boundary Current off Abaco Island, Grand Bahama on the density surface representative of the Labrador Sea Water (σ1.5 = 34.67, approximately 1700 meters). The time series shows the arrival of cold, fresh Labrador Sea Water in late 1994, which steadily extends offshore through the 2003 cruise.

Figure 6: Transport of the Deep Western Boundary Current offshore of Abaco Island. a) Baroclinic transport, relative to an assumed level of no motion at 800 dbar, and absolute transport integrated between 800 dbar and 4800 dbar and between mooring sites B and D. b) Absolute transport from the IES combined with the bottom pressure measurements compared to absolute transport integrated from the observations of the coincident current meter line. Because the current meter data was only available at 1200 dbar and below, the transports in this panel are integrated only over 1200-4800 dbar. Also shown is the transport determined by calculation dynamic heights from the temperature sensors moored alongside the current meters, utilizing the same bottom pressure sensors for the barotropic reference as were used with the IES data. Current meter and dynamic height mooring estimates are dotted after February 1997 because the mooring at site B lost its top portion at that time. Units are in Sverdrups (1 Sv = 106 m3 s-1).

3. Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)

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PROJECT SUMMARY

Overview

As a NOAA contribution to the global network of ocean time series reference stations, an air-sea flux buoy has been deployed in the Kuroshio recirculation gyre at 144.5E, 32.3N since June 2004. The buoy monitors air-sea heat, moisture, and momentum fluxes, and surface and subsurface temperature and salinity. In June 2005, we included additional subsurface instrumentation, and a pCO_2 system to monitor carbon flux. The site is within the NSF-funded Kuroshio Extension System Study (KESS) domain and KESS has provided ship time, equipment and personnel for mooring operations. In addition, KESS is providing important oceanic data including profiler floats and a line of profiler moorings. These KESS data will be used in conjunction with the KEO mooring to evaluate processes affecting the heat content and strength of the recirculation. We plan to add an ADCP mooring to monitor the heat balance at the KEO site. Collaborations with Japanese PIs have begun and a formal partnership between JAMSTEC and NOAA/PMEL for developing and maintaining the KEO array is being developed.

Scientific Rationale

The Kuroshio, the North Pacific's poleward flowing western boundary current, separates from the coast near 35ºN and becomes an eastward flowing jet, the Kuroshio Extension (KE). The KE represents the entrance region of the Pacific storm track and is characterized by some of the largest air-sea fluxes found in the entire North Pacific. It is one of the largest sinks of carbon in the North Pacific and has the characteristic maxima lobes of latent, sensible, and net surface heat loss. The net surface heat loss is particularly large during winter when the zenith angle of solar radiation is low and cold, dry continental air blows across the warm KE waters. Wintertime net surface heat losses average 330 W/m^2, and instantaneously these fluxes can be much higher (Fig. 1).

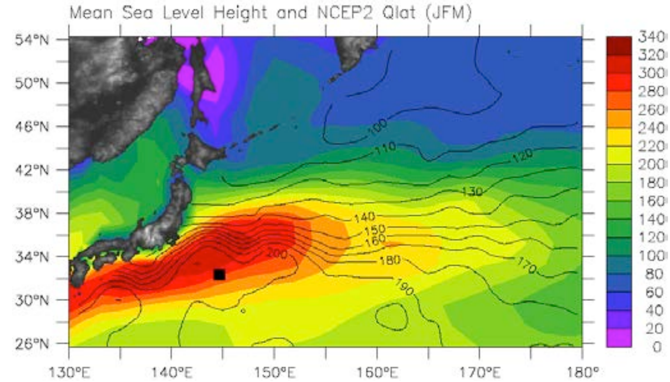

Fig. 1. Climatological wintertime (January-March) latent heat flux and sea level height in the Kuroshio Extension region. The KEO site is indicated by a black square. Sea level height contours can be interpreted as surface geostrophic streamlines of flow.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby the input of excess heat at the top of the atmosphere in the tropics is carried poleward by a combination of the oceanic and atmospheric circulations (e.g., Trenberth and Caron 2001). In the subtropical North Pacific, a significant fraction of this heat is transported poleward by the Kuroshio. At the KE, heat is transferred from the ocean to the atmosphere. North of the KE, more heat is carried poleward by the atmosphere (in large part through transient eddies, i.e., storms) than by the ocean. Since the partitioning of the meridional heat flux between the atmosphere and ocean is closely related to KE air-sea interactions, fluctuations in the latter are surmised to impact the climate variability of the North Pacific basin.

As with the Gulf Stream in the North Atlantic, the KE is highly variable, featuring large-amplitude meanders that can pinch off to form anti-cyclonic warm-core eddies north of the jet and cyclonic cold-core eddies south of the jet. It carries 140 million cubic meters (140 Sv) of warm water eastward into the North Pacific. Wind driven Sverdrup transport accounts for about a third of this transport; the other 90 Sv is due to a tight anticyclonic recirculation gyre south of the jet whose size varies on seasonal-decadal time scales. At the center of the recirculation gyre, the thermocline is deep. During spring and summertime, a seasonal mixed layer can form. Wintertime convection erodes this stratification producing a thick (up to 400 m thick) isothermal ~17C surface layer, termed Subtropical Mode Water (STMW). The STMW acts as a reservoir of heat. After it is isolated beneath the seasonal thermocline, it retains its water mass characteristics, reemerging the following winter to once again interact with the atmosphere. Through this "re-emergence mechanism", mode water formed in a given winter is expected to affect SST in the subsequent fall and winter. Mode water formation is also associated with the sequestering of carbon. Large dust clouds blowing eastward off Asia are visible in satellite images and can be traced all the way across the Pacific basin. Asian dust is rich in iron and other nutrients. With the KEO carbon flux system, we hope to monitor whether the carbon cycle's biological pump is affected by the passage of these clouds.

The KEO site is at 144.5°E, 32.3°N on the southern side of the Kuroshio Extension in its recirculation gyre and is part of the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) time series reference sites. With surface currents of almost 3 knots (~150 cm/s), a typically rough sea state, and lying in the Jet Stream's storm track, the KE is an extremely difficult region to observe. Ships have been the traditional platform for observing air-sea interaction in western boundary currents. However research cruises typically last no more than a month or two, and measurements from research ships and vessels of opportunity are biased towards good weather. With the successful first year deployment, the instrumentation of the KEO mooring was increased to include a carbon flux system and additional subsurface sensors as described below in Section 2.1. The KEO mooring is serving a wide community of climate sciences both in the US and in Japan. It is expected to provide a reference time series for comparison with numerical weather prediction products as well as satellite products. It is also expected to provide new insights into the air-sea interactions within this climatically important region.

Addressing NOAA's Program Plan

The KEO buoy is a contribution to the network of Ocean Reference Stations in a key region for air-sea interaction and therefore directly addresses the sixth element of the Program Plan for Building a Sustained Ocean Observing System for Climate (Ocean Reference Stations). As this mooring also carries a Carbon Flux sensor, this project directly addresses the eighth element "Ocean Carbon".

Management in Cooperation with International Panels

The KEO site has been endorsed by the International Time Series Science Team (co-chaired by R. Weller), which reports to the Ocean Observations Panel for Climate (OOPC). The two primary international ocean carbon research programs are the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere (SOLAS) programs. Both groups strongly recommend carbon time-series measurements and are very supportive of NOAA's efforts to develop a global pCO2 mooring network. The KEO mooring is an important part of that effort. Time-series carbon measurements are also a key element of the United States research programs like the Ocean Carbon and Climate Change Program (OCCC).

Responsible Institution

NOAA Pacific Marine Environmental Laboratory is the responsible institution for this project.

Websites

KEO website: http://www.pmel.noaa.gov/keo/

Partnerships

The KEO project has several strong partners. The KEO buoy is an element of the OceanSITES network of reference sites and therefore is partners with other buoy programs in the network (e.g. stratus, NTAS, HOT, TAO/TRITON,…). TAO and the NSF-funded Kuroshio Extension System Study (KESS) are particularly close working partners. The buoy was originally purchased under the now-complete NOAA OGP funded TAO-Eastern Pacific Investigation of Climate (EPIC) project. Professional staff supported by the KEO project are drawn from the pool of professional staff that participate in the TAO program. Located within the KESS array and within 10 km of N. Hogg's subsurface profiler mooring, the KEO buoy is contributing scientifically to the KESS experiment. KESS in turn has provided ship time, technicians and equipment for mooring operations. After the final KESS recovery cruise in June 2006, ship time will be provided through JAMSTEC. Partnership with JAMSTEC during FY05 resulted in a science meeting at JAMSTEC, "KESS and Beyond" co-chaired by Drs. Cronin and Ichikawa. Prof. Kubota has asked Cronin to collaborate on a project titled "KESS-flux" and Drs. Ichikawa, Konda, and Tanimoto have developed a plan to deploy a surface buoy, much like KEO, near the KEO site in order to better assess how satellite measurements can compare to in situ point measurements. Because KEO carries a carbon flux system, the KEO project also is a partner to NOAA's Global Carbon Cycle Program. This partnership is represented by co-PI Sabine.

FY2005 PROGRESS

KEO Buoy Performance Statistics

FY2005 included the first full deployment year of the KEO mooring. The mooring is a slack-line mooring with 1.4 scope and 500 m of fairing. During the June 2005 turn-around cruise, the buoy and top 750 m were recovered and replaced without releasing the mooring from its anchor. The full suite of meteorological measurements on the first-deployment of the KEO buoy included: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. Surface and subsurface measurements included sea surface temperature and salinity at 1 m, subsurface temperature at 11 depths down to 500m, subsurface salinity at 8 depths down to 400m, and pressure at 100 m, 300m, and 500 m. Because the mixed layer can be more than 400 m thick during wintertime, for the second deployment, we added 16 extra modules so that subsurface temperature has roughly 25 m depth resolution, salinity has ~50-75 m resolution, and subsurface pressure (to remap the slackline depths) has 75 m resolution. In addition, 3 current meters were attached at 5 m, 15m, and 35 m to monitor the near surfae currents. The year 1 and year 2 KEO mooring diagrams are both shown in Fig 2.

KEO data (Fig 3) has had an excellent data return, During the first deployment year, surface data had 100% data return, while subsurface data had 90% data return due to failure from the 75 m module. For FY05, the surface data has greater than 99% data return, and subsurface data return of 91%.

2.2 Data Management

Daily-averages of nearly all data (surface and subsurface) are telemetered to PMEL and made available in near-realtime from:

http://www.pmel.noaa.gov/keo/data.html

Because the KEO array is at this time an array of one buoy, the data are being withheld from the Global Telecommunications System (GTS) so that they can be used as an independent validation in comparisons with satellite and numerical weather prediction (NWP) fields. This decision will be reviewed periodically. High-resolution surface and subsurface data will be made publicly available through the KEO website within 6-months of recovery. At this point there is no user registry and so we have no way of monitoring the number of data downloads. This will likely be reviewed in FY06.

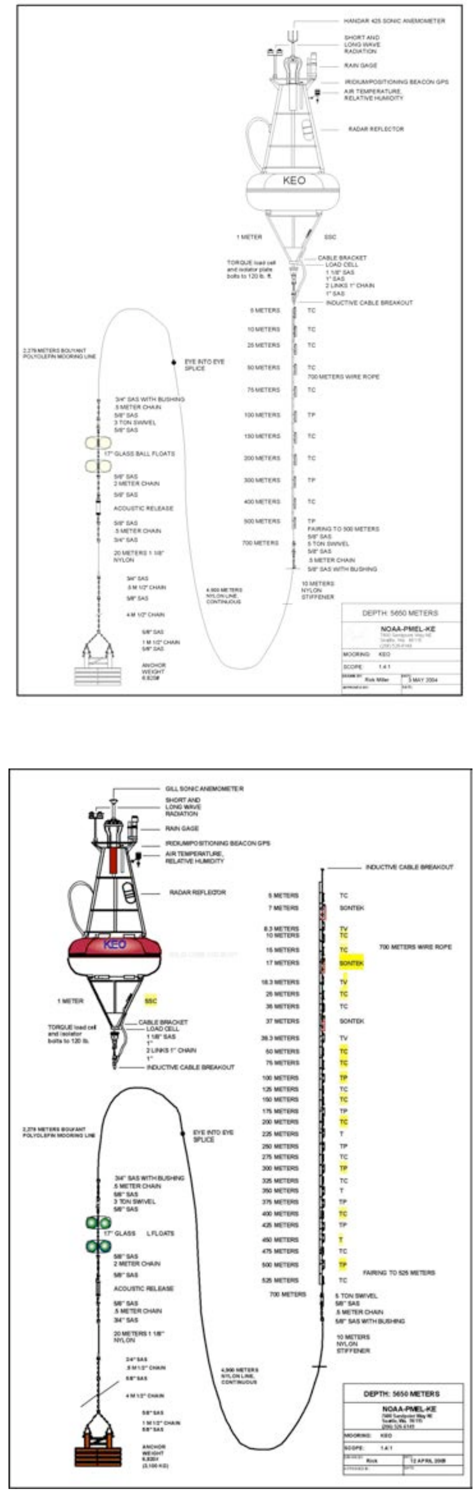

Fig.2 KEO diagram for the first deployment year (top panel) and for the second deployment year (bottom panel). Telemetered subsurface measurements are highlighted in the diagram on the right.

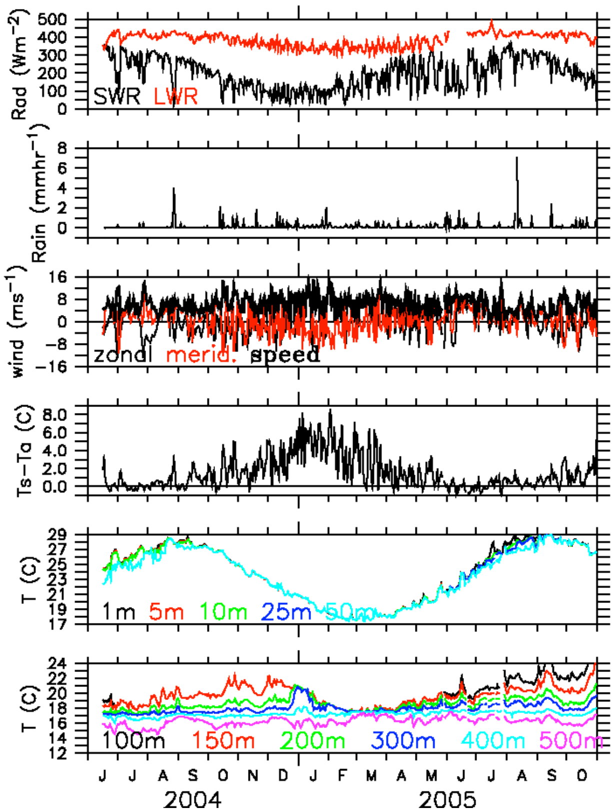

Fig. 3 KEO daily-averaged data through October 2005.

2.3 Logistics

The upper 700 m of the KEO mooring was recovered and refreshed as a piggy-back project on the KESS mooring cruise aboard the R/V Revelle with N. Hogg (WHOI) and S. Jayne (WHOI) as chief scientists. KESS also supported KEO by providing additional mooring technicians and equipment (winch, …). The KEO project is very grateful for the support provided by KESS. The PMEL scientific party included 1 mooring technician (M. Strick), a TAO programmer (S. Moon), and the KEO PI (M. Cronin). The final KESS cruise will be in May 2006. In January 2007, the KEO mooring will be refreshed aboard the Japanese ship Mirai, with Dr. Ichikawa as chief scientist.

2.3 Research Highlights

Large air-sea temperature differences can be seen in the KEO time series (Fig. 3) from October through March. Heat fluxes associated with cold-air outbreaks can contribute to explosive cyclogenesis, yet are often poorly modeled and can contribute to systematic biases in seasonal and climatological NWP flux estimates. KEO data are being used to compute air-sea heat fluxes for comparisons with the J-OFURO satellite derived flux products (Kubota 2005, personal communications).

As can be seen in Fig. 4, the Kuroshio Extension appears to have switched from a quasi-stable path-state, to an unstable path state. Periods with quasi-stable path, tend to have larger eastward surface transport, more northern zonal-mean path, and an elongated recirculation gyre; while periods with the unstable path tend to have a weaker eastward surface transport, more southern mean path, a contracted recirculation gyre. The KEO site is well-placed for investigating the processes affecting the recirculation gyre's heat content and their relationship to the state of the system.

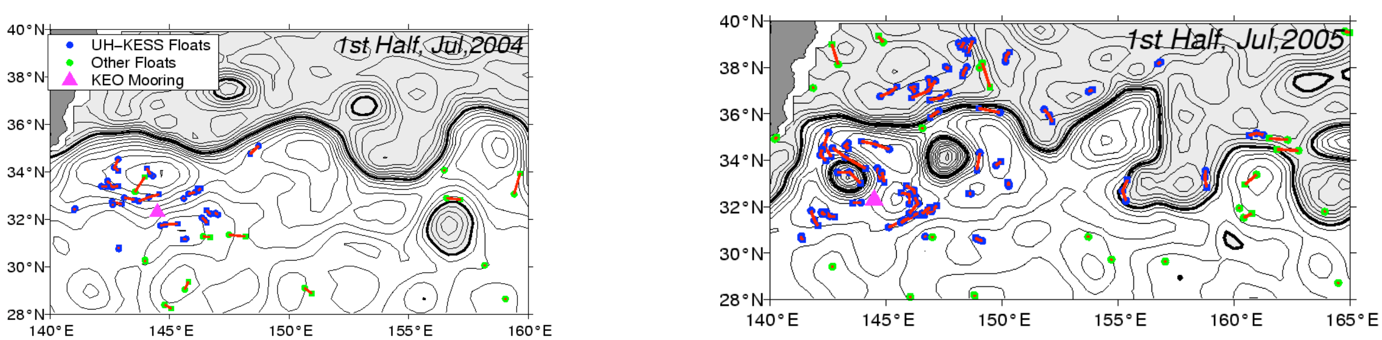

Fig. 4. Wintertime (January-March) latent heat flux and sea level height in the Kuroshio Extension region during 1996 (top) and 2004 (bottom). The KEO site is indicated by a black square. Sea level height contours can be interpreted as surface geostrophic streamlines of flow. The KEO-2 site described in Add-Task-2 is indicated by a gray square.

4. Weddell Sea Moorings

Arnold Gordon
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PROJECT SUMMARY

This project maintains three deep and bottom water focused moorings south of the South Orkney Islands in the Northwest Weddell Sea to provide a time series of the combined outflow (currents and temperature/salinity) of Antarctic Deep and Bottom Water drawn from various sites within the Weddell Sea. The moorings were initially installed and maintained as part of the Consortium on Oceans Role in Climate: AbRupt climate CHangE Studies (CORC-ARCHES) Southern Ocean Modern Observations program.

First installed in April 1999, the moorings are serviced using ship time made available by other programs, primarily through the National Science Foundation Office of Polar Programs (OPP), and principal investigators funded by OPP who graciously allow our team to sail on their cruises. As time and resources allow during the mooring maintenance cruises, CTD/tracer stations are occupied at the mooring sites and at stations distributed along a line between the mooring locations (Figure 1).

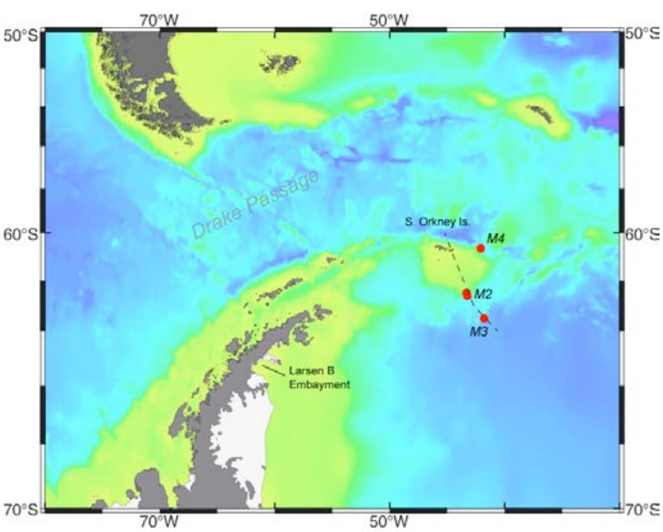

Figure 1. Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line).

The CORC-Arches Weddell mooring program was designed to service the moorings every two years, or more frequently if ship time were available.

Addressing NOAA's Program Plan

This project addresses NOAA's Program Plan by establishing and maintaining an in situ Ocean Reference Station in the undersampled Weddell Sea. The moorings, repeat CTD/Tracer stations, and analysis of regional data sets are designed to address in part the dearth of long time series data in this potentially climatically sensitive region of the Southern Ocean. The Southern Ocean in general and the Weddell Gyre in particular are regions of vigorous air-sea-ice interaction and water mass transformation. The few observations we have indicate a broad spectrum of variability with potentially large and global consequences. The processes involved are believed to be quite sensitive to small changes in forcing and have the potential to amplify changes in climate forcing due to ice-ocean feedback. The precise mechanisms of climate variability in the Southern Ocean are not well understood, nor adequately observed largely due to the difficulty in obtaining the appropriate observational data sets. Coupled models of the ocean-atmosphere-ice system do not perform well in the Southern Ocean region. Fundamental processes of water mass transformation, such as coastal shelf water formation and overflows are often poorly resolved or absent in the current generation of climate models. The stability and variability of the different deep water formation processes are poorly understood but might turn out to be crucial for the global climate system.

Responsible Institutions

The project is carried out by personnel from the Division of Ocean and Climate Physics, Lamont-Doherty Earth Observatory of Columbia University.

Interagency and International partnerships

This project relies on opportunistic use of ship time to service the moorings and occupy the CTD stations on a widely varying schedule. Because the moorings are located in a seasonal sea ice zone with unpredictable ice coverage, an ice-capable vessel is required for the field work. We have benefited greatly from the cooperation with NSF/OPP and several of their investigators. In conjunction with this support from OPP, we have recently entered into a scientific collaboration with E. Domack to place instruments on several of his sediment trap moorings in the Larsen B embayment and in front of the Larsen C ice shelf. This pilot study is aimed at determining the feasibility and design of a more comprehensive monitoring array in this sensitive region of deep and bottom water formation.

In February 2001, we were the guests of the Brazilian Antarctic Program on board their vessel Ary Rongel.

We have recently entered into a preliminary collaborative agreement with investigators at the British Antarctic Survey (BAS) to establish a joint expansion of the Weddell mooring array, as part of which BAS will provide vessel time for servicing all of the moorings beginning in the austral summer of 2006.

FY 2005 PROGRESS

The CORC-Arches Weddell mooring program was designed to service the moorings every two years, or more frequently if ship time were available. After their initial deployment and an innaugural CTD/tracer section in 1999, the moorings were visited in April 2000, February 2001 and December 2001. No ship time was available in 2002, and, while ship time was made available to us in 2003 and 2004, severe sea ice conditions prevented access to the moorings.

In March of 2005, we succeeded in reaching the mooring sites, recovering two, and redeploying a mooring at the southernmost site M3 (Figure 1). Weather and time constraints dictated that M4 be left in place, and that M2 be recovered but not redeployed.

The new data set extends the Weddell Sea time series to nearly 6 years overall (Figure 2). Several CTD stations were occupied near the mooring sites and at several stations between the mooring locations.

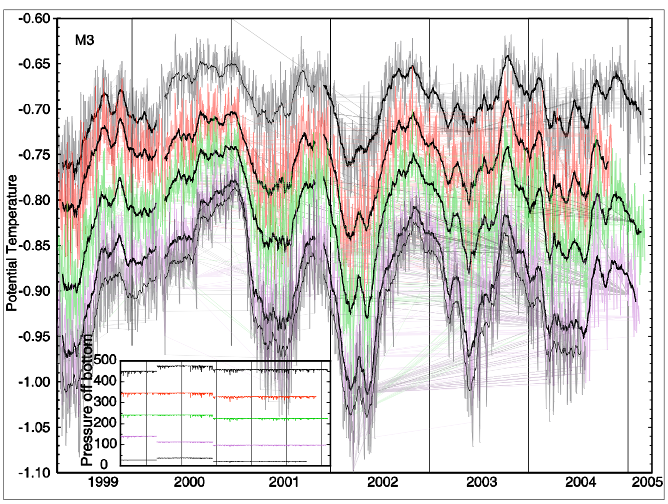

Figure 2. Potential temperature records from mooring M3 (see Fig 1 for location). The inset depicts instrument distance from the bottom. Mooring depth is nominally 4600 m.

Preliminary analysis of the near-bottom potential temperature and salinity records of the moorings from April 1999 to November 2001 suggested a seasonal cycle, albeit with some year-to-year variability. These are likely a consequence of changes in the production of dense Weddell Sea bottom water associated with varying amounts or source changes of the shelf water component. In addition, cold bottom water events lasting 1 to 2 days are embedded in the 0.1 m/s mean isobath-following eastward flow. Adding the newly recovered data to the time series clearly reveals the seasonality of the deep temperatures, with longer period signals superimposed.

The newly recovered records continuously span more than 3 years in some cases, including the time period corresponding to the breakup of the Larsen B ice shelf of the eastern Antarctic Peninsula in early 2002. It has been hypothesized that the Larsen ice shelves play a significant role in the production of deep and bottom waters in the western Weddell Sea, so the Weddell time series may be uniquely positioned to investigate the oceanographic conditions leading up to and following the breakup of the Larsen B.

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5. High Resolution Climate Data From Research and Volunteer Observing Ships

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PROJECT SUMMARY

This project involves the measurement of direct high-resolution air-sea fluxes on two cruises per year and the development of a roving standard flux measuring system to be deployed on a series of NOAA and UNOLS research vessels to promote the improvement of climate-quality data from those platforms. An adjunct task is maintenance and operation of the C-band scanning Doppler radar and the stabilized wind profiling radar on the NOAA ship *Ronald H. Brown*. Because buoys and most ships and satellites rely on bulk methods to estimate fluxes, another aspect of this project is the use of direct measurements to improve the NOAA/COARE bulk flux algorithm. One cruise is the annual TAO buoy tending cruise to 95^o and 110^{o}W on the *Ronald Brown*, which occurs every fall. The second cruise, which also occurs in the fall, is the annual excursion to turn around the Stratus climate buoy at 20^{o}S 85^{o}W. A full suite of direct, inertial-dissipation, and bulk turbulent fluxes are measured along with IR and solar radiative fluxes, precipitation, and associated bulk meteorological properties. This effort represents a partial transition of research from the OGP CLIVAR PACS program to operations under the Climate Observations Program (COP).

The project development is the result of a recent NOAA-sponsored workshop on high-resolution marine measurements (Smith et al., 2003, *Report and Recommendations from the Workshop on High-Resolution Marine Meteorology*, COAPS Report 03-01, Florida State University, pp38) which identified three important issues with the planned NOAA air-sea observation system: 1) the need for a data quality assurance program to firmly establish that the observations meet the accuracy requirements, 2) the need for observations at high time resolution (about 1 minute), 3) and the need to more efficiently utilize research vessels, including realizing their potential for the highest quality data and their potential to provide more direct and comprehensive observations. For seasonal time scales, the net air-sea flux (sum of 5 flux components) must be constrained within 10 Wm^{-2}. Buoys and VOS systems are required to operate virtually unattended for months, so considerations of practical issues (e.g., power availability, instrument ruggedness, or safe access) are balanced against inherent sensor accuracy and optimal sensor placement. As discussed above, an important function of the in situ measurements is to provide validation data to improve NWP and satellite flux fields. Here, high time resolution and more direct observations are invaluable for interpreting surface flux measurements and diagnosing the source of disagreements; such information can be provided by suitably equipped research vessels (R/V). Thus, the accuracy of buoy and VOS observations must be improved and supplemented with high-quality, high time resolution measurements from the US R/V fleet (which is presently underutilized). The necessity for both high time resolution and high accuracy places extreme demands on measurements because some sources of error (such as the effect of ship flow distortion on wind speed) tend to average out over a large sample. To accomplish this task will require a careful intercomparison program to provide traceability of buoy, VOS, and RV accuracy to a set of standards.

This project directly addresses the need for accurate measures of air-sea exchange (Sections 5.2 to 5.4, *Program Plan for Building a Sustained Ocean Observing System for Climate*. The project is a joint effort by ETL and Dr. Robert Weller of the Woods Hole Oceanographic Institution (WHOI). NOAA COP funds the ETL component and Dr. Weller is seeking NSF fund for the WHOI component. The ETL Air-Sea Interaction Group website can be found at: http://www.etl.noaa.gov/et6/air-sea/. ETL also cooperates with Dr. Andy Jessup (APL University of Washington) on radiative sea surface temperature measurements, Dr. Frank Bradley (CSIRO, Canberra Australia) on precipitation, Drs. M. Cronin and N. Bond (PMEL) on buoy-ship intercomparisons and climate variability analysis, and Dr. Mike Reynolds (DOE BNL) on radiative fluxes. A new website is under construction for this project (High Resolution Climate Observations). The website is planned to contain a handbook on best practices for flux measurements plus a database of high-resolution flux data. This work will be closely monitored by the new WCRP Working Group on Surface Fluxes (WGSF) which is chaired by C. Fairall. This will give the project high visibility in the CLIVAR, GEWEX, and SOLAS programs. This project will be managed in cooperation with JCOMM (and other) panels.

FY2005 PROGRESS

For the *Ronald Brown* C-band and wind profiler radar project, hardware upgrades and routine maintenance was performed on the wind profiler at Woods Hole Oceanographic Institution prior to the NOAA Stratus 2005 cruise planned for October 2005. While the ship was in WHOI Engineer John Novak RadTech Inc. installed the transmitter following its repair. Novak was joined by two engineers from SIGMET, Inc. Dan Wolfe and this group spent two days upgrading the C-band radar software and solving several software/hardware problems with the motion compensation for the pedestal. The software licenses and maintenance were also continued with SIGMET. The C-band radar and wind profiler are also to be operated during the Bob Molinari buoy deployment cruise in the Atlantic in the summer of 2006 (this is the *AMMA/Saharan Dust* cruise).

ETL completed two research cruises as planned: the annual TAO tender cruise to 95 and 110 W longitude in the equatorial Pacific on board the R/V *Ronald H. Brown* and the joint ETL/WHOI cruise to the climate reference buoy (25 S 80 W), also on board the Brown. Two related research highlights will be described here. One of the goals of this project is promoting the accuracy of buoy-based climate reference observations. ETL ship measurements from previous deployments have been used to evaluate TAO buoy and the WHOI Stratus buoy. A very detailed comparison has been done with 9 ETL cruises to the EPIC enhanced TAO buoys in the East Pacific and the buoys were found to meet the WCRP standard of 10 Wm^{-2} for 1 week averages of net heat flux (described in *Accuracy of buoy-derived and NWP surface heat fluxes in the Tropical Pacific*, Cronin et al., submitted to JGR). A paper on ship-buoy comparisons for the WHOI flux reference site has also been submitted. The second research highlight is a pilot evaluation of research vessel near-surface meteorology and bulk flux estimation data quality. This also was based on the 9 TAO cruises and 3 cruises to the WHOI Stratus location. Three ships were examined: NOAA ships *Ronald H. Brown* and *Ka'imi Moana* and the UNOLS ship *Roger Revelle*. The results are summarized below:

- Comparison of ETL sensors across entire R/V pool suggests no significant bias in ETL data.
- Basic sensors on R/V's within or close to required accuracy
- Some problems with sensor placement (e.g., RHB 1999-2003)
- Some problems with early ship-ETL intercomparions (KAI and RHB) indicate poorly performing sensors often not replaced immediately.
- Better monitoring or redundancy is required for R/V's to meet climate goals

Considerable progress was also made on developing the portable flux standard and implementing ship and buoy intercomparisons for quality assurance. Dr. Frank Bradley of CSIRO Canberra Australia visited ETL for a month in the summer of 2005 to work on the flux measurement handbook. Considerable progress was made and a draft was circulated among coauthors. The first review draft will be substantially complete by November 2005. It is planned to circulate a second draft in time for feedback at the SAMOS meeting in Boulder in April 2006. A website for the project has been begun (http://www.etl.noaa.gov/programs/oceanobs/)

Production of the roving flux standard is well underway. We plan to upgrade one of the existing ETL flux systems to create the portable standard (i.e., rather than build an entire new system from scratch). The upgrade will feature two parts: 1) convert from a network cabled sensors to wireless transmission and 2) improve the radiative flux and navigational measurements. The first step is to simplify the shipping, installation, and tear down process so that it is cheaper and more practical to operate on a series of ships. The second step is necessary to close some accuracy shortcomings, balance the sources of error between radiative and turbulent fluxes, and take advantage of recent developments in GPS technology.

- Wireless hardware was acquired in FY2005. A field test was conducted in Boulder in June and a prototype system was installed on the *Brown* at WHOI. We will do the fall Stratus cruise with the prototype system. Following evaluation of the results, the wireless components will be engineered for the portable system.
- A market survey of pitch/roll compensation systems for the radiative flux measurements was conducted and a suitable system could not be located for a reasonable cost. A system was designed inhouse at ETL and components were ordered. The system will be built in 2006.
- In January 2005 the ETL flux system was installed and operated on the UNOLS R/V *Seward Johnson* to participate in the RICO field program. This gave us an opportunity to evaluate two commercial full 6-compenent navigation systems (PosMV and JAVAD) by comparing their motion outputs with the ETL system. Both systems compared well with the ETL system and would be suitable for the portable standard.

The PI of this project has been appointed to chair the WCRP Working Group on Surface Fluxes. He also serves on the International Geophysical Union International Climate Dynamics and Meteorology Working Group A (Boundary Layers and Air-Sea Interaction). In 2004 he was invited to join the SOLAS Focus 2 (air-sea flux physics) Working Group to develop the Surface Ocean-Lower Atmosphere Study (SOLAS) International Implementation Plan and has been named to the US SOLAS Advisory Group.

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6. U.S. Research Vessel Surface Meteorology Data Assembly Center

James J. O'Brien, Mark A. Bourassa and Shawn R. Smith
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PROJECT SUMMARY

Accurate estimates of turbulent air-sea fluxes over the global oceans are necessary for ocean modeling, climate modeling, and are a key component of NOAA's Climate Observation Program (e.g., WGASF 2000, NOAA 2005). The Research Vessel Surface Meteorology Data Assembly Center (hereafter the DAC) evaluates the accuracy of turbulent fluxes from in-situ observations, satellite observations, and global gridded fields [e.g., FSU fluxes, numerical weather prediction (NWP) center reanalyses]. These activities specifically target components of NOAA's strategic plan to quantify uncertainties in our understanding of the global climate system.

The unique component of the DAC activities is the source of in-situ data: quality-evaluated, shipboard automated meteorological and oceanographic system (SAMOS) observations collected by research vessels (R/Vs) and select voluntary observing ships (VOS). A SAMOS is typically a computerized data logging system that continuously records navigational (ship's position, course, speed, and heading), meteorological (winds, air temperature, pressure, moisture, rainfall, and radiation), and near-surface oceanographic (sea temperature, conductivity, and salinity) parameters while the vessel is at sea. Measurements are recorded at high-temporal sampling rates (typically 1 minute or less). The high sampling rate allows for more accurate estimates of the turbulent air-sea fluxes (Smith et al. 2001) and makes SAMOS data ideal for validating flux fields from NWP models (Smith et al. 2001, Renfrew et al. 2002). In addition, SAMOS observations have proven to be an ideal source of validation data for new satellite systems (Bourassa et al. 1997, 2003). The fact that R/Vs tend to operate in areas remote from normal shipping lanes increases the value of these data for validation studies. Future inclusion of vessels operating in polar regions will allow evaluation of fluxes under extreme environmental conditions.

Current funding from the NOAA Office of Climate Observation (OCO) is provided to COAPS via the Woods Hole Oceanographic Institution (WHOI) Cooperative Institute for Climate and Ocean Research to support the DAC's data stewardship activities. The DAC has worked with partners at WHOI through a pilot project to develop a daily ship-to-shore-to-user data pathway for SAMOS observations. Throughout the development of the SAMOS data stewardship pathways, the DAC has continued to evaluate the quality of delayed-mode SAMOS observations from the NOAA vessels *Ronald Brown* and *Ka'Imimoana* (e.g., Rolph and Smith 2005 a, d). Initial evaluation of ASIMET (Hosom 1995) equipped VOS is also underway. All shipboard observations are evaluated using an improved automated and visual quality processing system developed to support the SAMOS initiative (Smith 2004a, b). Initial testing of the new system is underway as part of a 2005 pilot project.

All activities of the DAC are the responsibility of personnel at COAPS. As an active member of the SAMOS initiative (Co-PI Smith is chair), the DAC continues to build partnerships with the ship technicians, vessel operators (e.g., University-National Oceanographic Laboratory System [UNOLS], NOAA Marine and Aviation Operations [MAO]), and international data centers. We have a strong collaborative relationship with WHOI that includes Robert Weller (research moorings, fluxes), David Hosom and Frank Bahr (VOS ASIMET program), and Barrie Walden (R/V IMET program). The DAC has ongoing collaboration with members of several JCOMM panels, the WMO VOSClim program, the WCRP Working Group on Surface Fluxes (Smith is a member), the IODE GOSUD project, both the U. S. and international CLIVAR program, GOOS, and the Ocean.US IOOS-DMAC.

DAC activities are managed in accordance to the Ten Climate Monitoring Principles outlined by the Global Climate Observing System (GCOS 2004). Since our inception with WOCE and TOGA-COARE, the COAPS R/V data center has emphasized the importance of metadata to fully document our data sets (3rd principle). We have a clear focus on data quality and have applied a number of innovative quality assurance (QA) techniques for R/V data (4th principle). The DAC plans to recruit vessels that operate in the remote oceans which will increase access to in-situ measurements (e.g., radiation, heat fluxes) that are currently hard to obtain (7th principle). Through the SAMOS initiative, the DAC has sought input from scientists, technicians, data and archival experts, and policy makers to ensure that the design and implementation future DAC data quality and distribution practices serve a broad user community. The DAC addresses the 10th principle by continuing to provide free and open access to all R/V data, metadata, and documentation through the COAPS DAC (http://www.coaps.fsu.edu/RVSMDC/).

Significance of DAC

The DAC provides scientific stewardship of SAMOS observations collected by R/Vs and VOS. All data receive uniform QA processing and the data are distributed with common formatting and metadata. Operators of R/Vs and VOS will benefit from near-real time feedback on their system's operation and data quality. Under the SAMOS initiative, individual chief scientists will no longer be required to manage the meteorological data from their scientific cruises, and they will benefit from rapid access to quality processed observations to use in their research. In keeping with the stewardship goals of IOOS, the DAC will ensure that both the QA processed data and the original observations are housed and available at one or more national archive centers. This policy will allow future generations to apply new QA and data assimilation techniques as they are developed. NOAA and other agencies funding SAMOS installations can expect to see value added to their capital investment in shipboard instrument systems.

In terms of data access and volume, the DAC will significantly increase the number of high-quality meteorological observations available for independent validation studies. In a given year most blue water R/Vs are deployed for 250-300 days. Assuming a one-minute sampling rate, the result will be approximately 400,000 individual wind, sea and air temperature, pressure, humidity, and radiation observations per vessel. When fully implemented for the U. S. R/V fleet, the DAC will be providing millions of observations per year for use in satellite and model validation, operational activities, and a wide range of ocean, atmosphere, and climate research.

Finally, the DAC activities address several performance measures and milestones outlined the Program Plan for NOAA OCO (NOAA 2005). The core of the DAC's activities address NOAA's plan to "maintain sensor suites on a small core of vessels as the highest quality calibration points for validation of other system measurements". SAMOS data evaluated by the DAC target performance measures related to improving the accuracy and quality of heat, momentum, and fresh water fluxes, along with the meteorological and near ocean surface parameters needed to calculate the fluxes. The DAC will be involved with the QA of new SAMOS deployments on VOS in support of NOAA's goal to improve meteorological measurements on ships of opportunity. Finally, the DAC emphasizes long-term data stewardship, supports the IOOS-DMAC, and provides the highest quality SAMOS data for use in new and ongoing data validation activities.

FY 2005 PROGRESS

SAMOS Initiative

The SAMOS initiative was developed based on the 13 recommendations of the Workshop on High-Resolution Marine Meteorology held in Tallahassee, FL on 3-5 March 2003 (Smith and Reynolds 2003; http://www.coaps.fsu.edu/RVSMDC/marine_workshop/Workshop.html). A follow-on workshop was hosted by NOAA OCO in Silver Spring, Maryland on 15 and 16 April 2004 (Smith 2004a, b). The purpose of the second workshop was to discuss implementation of the recommendations. In FY2004 the DAC was established at COAPS to coordinate the collection, QA, distribution, and future archival of SAMOS data collected on U. S. research vessels and select VOS.

In 2005, the DAC, in collaboration with WHOI and the Scripps Institution of Oceanography, established a pilot project to design a ship-to-shore-to-user SAMOS data pathway. The pathway (Fig. 1) now supports data transmission from a research vessel at sea to the DAC on a daily basis. Preliminary versions of the SAMOS data are made available to the user community within 5 minutes of receipt of the daily data message by the DAC. The preliminary data undergo common formatting, metadata augmentation, and automated QA. Visual inspection and further scientific QA will result in a research quality SAMOS product. The research quality product will include delayed data reports and will be available within a few weeks of the initial data collection date. The first research products from the pilot project will be available in late 2005.

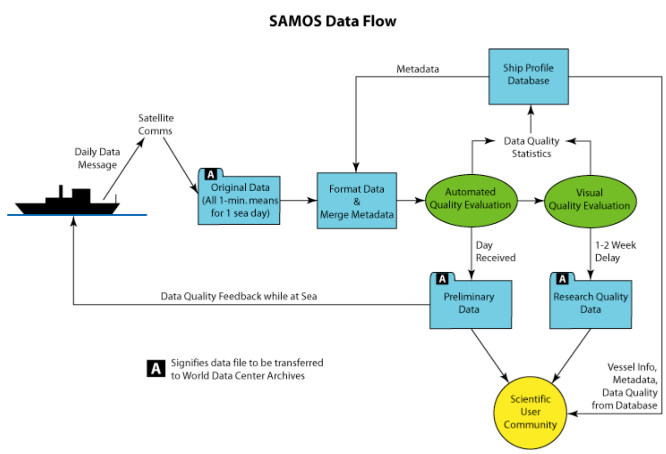

Fig. 1: Data flow diagram for SAMOS 2005 pilot project.

The DAC has spearheaded the development of a metadata profile for each ship participating in the SAMOS initiative. A draft SAMOS metadata standard has been developed and is being reviewed during the pilot project. Each vessel's metadata profile is stored in a relational database designed by DAC personnel. Essential metadata (e.g., 3-axis instrument location, data sampling rates, averaging periods, etc.) from each ship are automatically merged with incoming SAMOS observations (Fig. 1). Development of a community access portal to the metadata database is underway.

A founding principle of a data center is the ability to track all data sets and manage different versions of the data. The DAC has established protocols to track data through each processing step and to monitor for duplicate and delayed data arrivals. Preliminary SAMOS observations are available to data users 5 minutes after receipt of the data at the DAC, and visually inspected research quality products will be available a few weeks after receipt. In addition, all the QA flags from both the automated and visual processes are tracked and stored within the database for each day of SAMOS observations.

The DAC continues to develop both web (http://samos.coaps.fsu.edu/) and ftp data distribution services for the quality controlled RV data. Currently all SAMOS data are available in netCDF format; however, we plan to distribute data in additional formats to meet user needs. Methods of disseminating QA information are under development (via web searches and semi-annual reports). The DAC is working with partners at NODC, NOAA CDC, and NCAR ensure that the original and quality assured data are available within national marine data archives.

Data processing

SAMOS observations are being received and processed on a daily basis for two WHOI vessels, the *Knorr* and *Atlantis*, as part of the 2005 pilot project. Preliminary netCDF files, which include common formatting, uniform metadata, and automated quality evaluation, are available for 9 May to present for the *Knorr* and 1 June

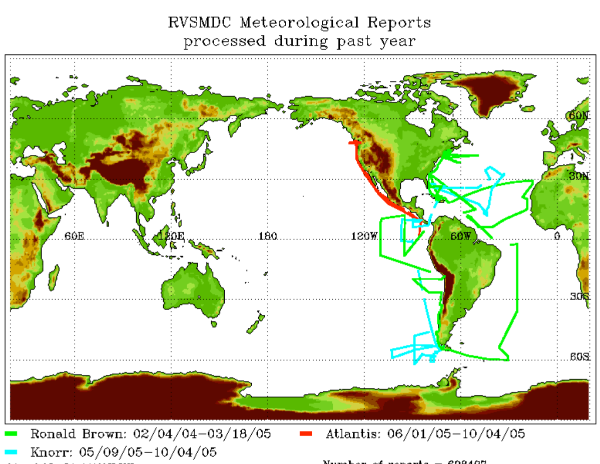

Fig. 2: Ship tracks for research vessel data passing quality evaluation at the DAC between October 2004 and September 2005. All data were sampled at 1-minute intervals by automated instrument systems. Knorr and Atlantis data were received and processed in near-real time.

to present for the *Atlantis* (Fig. 2). Access to preliminary files is available from http://samos.coaps.fsu.edu. In addition to the near-real time SAMOS data processing, the DAC continues to evaluate delayed mode observations from NOAA and select international vessels. Delayed-mode data have been processed for the *Ronald Brown* (Feb. 2004 – May 2005; Fig. 2) and the *Meteor* (June 2003 – May 2004; not shown). The observations from *Meteor* were collected and evaluated as part of our satellite validation efforts (Rolph and Smith 2005b) but are not available on our web site as we are awaiting distribution permission from Germany. Data from all the vessels are sampled at one-minute intervals and typically include the ship's position, speed, course, and heading along with standard meteorological parameters (e.g., ship- and earth-relative winds, air and sea temperature, atmospheric pressure, humidity, and shortwave and longwave radiation). Data coverage is concentrated around the Americas, with nearly 700,000 individual marine reports being made available to the community.

In the past year we have successfully restarted post cruise delivery of delayed-mode meteorological data between the *Ka'Imimoana* and the DAC. We are now in possession of data for Oct. 2004 – Mar. 2005 and will begin QC processing soon. In addition, we were able to work with partners at PMEL to obtain *Ka'Imimoana* data for the period 31 October 2001 – 17 August 2004. The problem with these files is that they are recorded in a wide array of data formats (differing by cruise) and it will take a large amount of the DAC's resources to place these data into a common netCDF format for quality evaluation. Due to the formatting issues, we will work on these *Ka'Imimoana* data as time and resources permit.

To date we have received meteorological data from five CLIVAR sponsored hydrographic cruises (see http://www.coaps.fsu.edu/RVSMDC/CLIVAR/). Using the new SAMOS data processing system, we will work to provide a minimum of automated quality control for CLIVAR cruises from international vessels. One of the five cruises was conducted by the *Ronald Brown*, so those data will undergo full automated and visual inspection by the end of 2005.

The value-added data and quality control reports (Rolph and Smith 2005a, d) are available from our center at http://www.coaps.fsu.edu/RVSMDC/. Shipboard data are also available via ftp://wocemet.fsu.edu/pub/woce/rv or pub/rvsmdc/rv and our DODS server (http://www.coaps.fsu.edu/RVSMDC/html/dods.shtml). We are committed to an open data sharing policy so data access is not restricted. Through supplemental funding through NOAA/ESDIM, a portion of the RVSMDC holdings are being subsampled for inclusion in the International Comprehensive Ocean Atmosphere Data Set (I-COADS; Worley et al 2005). These data will be provided in International Maritime Meteorological Archive (IMMA) format (Woodruff 2005). We have also opened communication with NODC and NCAR to ensure the archival of quality-evaluated data.

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7. Assimilation, Analysis and Dissemination of Pacific Rain Gauge Data: PACRAIN

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PROJECT SUMMARY

General Overview

This project supports NOAA's Office of Climate Observations (OCO)'s effort to "build and sustain the global climate observing system that is needed to satisfy the long-term observational requirements of the operational forecast centers, international research programs, and major scientific assessments". We also are continuing in our role as the Surface Reference Data Center (SRDC), a core program that supports the Global Precipitation Climatology Project (GPCP) and the Global Energy and Water Cycle Experiment (GEWEX). Our current and future efforts include expanding our mission to collect, analyze, verify and disseminate global rainfall data sets and products deemed useful for Operational Forecast Centers, International Research Programs and individual researchers in their scientific endeavors. Housed in the Environmental Verification and Analysis Center (EVAC) at the University of Oklahoma, the EVAC/SRDC has built upon work from past NOAA-supported projects to become a unique location for scientists to obtain scarce rain gauge data and to conduct research into verification activities. These data are continually analyzed to produce error-assessed rainfall products.

Rainfall data is particularly important in the tropics. Not only is it a tracer of latent heat, it is vitally important to the understanding of ocean properties as well, such as latent and sensible heat flux, salinity changes and attendant local ocean circulation changes. In addition, rain gauge observations from low-lying atolls are required to conduct verification exercises of nearby buoy-mounted rain gauges, many of which are funded by the OCO program.

Scientists need only to access the EVAC/SRDC web site http://www.evac.ou.edu/pacrain to obtain the most comprehensive Pacific rainfall data set anywhere and http://www.evac.ou.edu/srdc to obtain critical regional rain gauge data sets. Many of these regional data sets are impossible or impractical to obtain elsewhere. The EVAC/SRDC serves the research community by actively working with individual countries in environmentally important locations to help provide them with infrastructure, education and other short and long-term support. The return on this investment by NOAA has been significant in terms of enabling EVAC/SRDC to provide the scientific community with critical, one-of-a-kind rain gauge data sets and to have established ongoing mutually beneficial relationships that should lead to future collaborations. Past successes with this strategy have proven very worthwhile on a cost-benefit basis.

Due to the importance of tropical Pacific rainfall data to climate research and operational and climate forecasting we are intensifying our efforts by working collaboratively with the Pacific Island Global Climate Observing System (PI-GCOS) program to effectively and efficiently match the areas of commonality among both OCO's and PI-GCOS's objectives. One of these common areas is the strengthening of the existing Pacific observation climate networks for both atmosphere and ocean.

We are using the above strategy to expand our efforts to increase the rain gauge climate observing data base representing specific, environmentally critical locations. It is not our intention to collect all rain gauge data worldwide, but to assimilate rain gauge data 1) in environmentally critical locations (e.g. tropical Pacific), 2) where dense rain gauge networks exist and 3) where agreements can be made to help construct rain gauge networks in these critical locations. An experimental effort focused on the latter objective with the governments of individual Pacific Island countries has resulted in a large network of hundreds of new manual-read rain gauges located on various atolls and islands managed by the local Meteorological Service (refer to SPaRCE project; http://sparce.evac.ou.edu/). In addition, similar pilot projects using high tech tipping bucket rain gauges have produced a relatively dense rain gauge network on the island of Niue in the south Pacific and a critical all-weather observation platform on Pitcairn island in the south east Pacific. The success of these relatively low-cost efforts has motivated us to expand both and low instrumentation technology projects in collaboration with PI-GCOS to other Pacific Island locales.

It is our belief that by working directly with local Pacific Island meteorological services, we bring tangible benefits to the global climate research community through data base enhancement. In turn, the local meteorological services benefit directly through enhanced forecast products developed by the scientific community using these critical data sets.

To better accomplish these tasks, the Project Manager (i.e. P.M.; Mark Morrissey) of this project took leave from his University of Oklahoma position to become the first PI-GCOS coordinator headquartered at the Secretariat for the Pacific Regional Environmental Program (i.e. SPREP) in Apia, Samoa. During his 1.5 year tenure there (from January 2004 through May 2005) he helped consolidate the PI-GCOS program by working with and initiating various high priority PI-GCOS projects outlined in the PI-GCOS action plan. He coordinated the 10th Regional Meteorological Director's meeting hosted by the island nation of Niue and ran the 1st meeting of the PI-GCOS steering group. Since returning to the University of Oklahoma, the P.M. is working with the PI-GCOS program by focusing on building a sustainable basic climate instrument network in collaboration with the Pacific Island Meteorological Services. A pilot program has been conducted to assess the feasibility and practicality of distributing 55 high quality tipping bucket rain gauges donated by EVAC to various Pacific Island Meteorological Services. The initial results of this pilot strongly suggest that it should be expanded and managed in a collaborative manner with the current PI-GCOS coordinator at SPREP and the PI-GCOS Technical Support Project (TSP) headquartered at the New Zealand Meteorological Service. These initial results of comparisons with manual read gauges indicate that a close correspondence in daily rainfall accumulations. Note that these tipping bucket gauges are installed with data loggers and have the potential to allow a relatively small Pacific Island Meteorology Service to set up a large climate observing system providing high resolution data to the global research community. A complete description of an expanded version of this project is given in section II. b) of this document. We are also actively involved in data rescue activities and data quality control in collaboration with the New Zealand Institute for Research in Water and Atmosphere (NIWA) and the Australian Bureau of Meteorology (BOM). Periodic updates and news pertaining to the PACRAIN database are sent out via email and the database can be retrieved from http://pacrain.evac.ou.edu/. The data set is available in both monthly and daily versions.

In addition to the work above, we are working with the BOM to implement and verify a seasonal rainfall forecast tool being developed by BOM using an artificial intelligence/statistical method. Only through the use of the PACRAIN data base could the tool be used successfully in both forecasting and verification of the results.

We are also requesting additional funding under 'Added Tasks' that will complement our data collection and quality control efforts under PI-GCOS.

Addressing NOAA's Program Plan

This project falls under the Atmospheric Section of OCO that supports the U.S. contribution to the Global Climate Observing System (i.e. GCOS) plan. The U.S. GCOS program primarily focuses on PI-GCOS. This is noted by the following statement on the OCO web page:

"On the regional level, via State Department supported bi-lateral climate agreements with Australia and New Zealand, the program supports the Pacific Islands regional GCOS program; with the Pacific being of critical importance to climate (e.g., source of El Nino) and given the general sparseness of data from this critical climate region, a strong regional program in support of GCOS is a benefit to the global climate observing effort".

During the past 1.5 years, the P.M. of this project assumed the position of the PI-GCOS in Samoa. One very important outcome of the P.M.'s effort spent in this position was to develop a basic instrumentation plan that will provide quality climate data at high resolution in collaboration with the Pacific Meteorological Services. He also worked and is working closely with all involved in the PI-GCOS effort. As an example, the P.M. initiated and coordinated the 10th Regional Meteorological Service Director's meeting held during April 2005 hosted by the country of Niue.

Collaboration with international implementation panels and interagency and international partnerships

This project works very closely with the PI-GCOS Steering Group. In fact, the Steering Group was primarily organized by the P.M. of this project. We also work closely with the Global Ocean Observing System (GOOS) as well as the GCOS secretariat in Geneva at the World Meteorological Organization (WMO). As an international project, groups we closely work with also include SPREP, the New Zealand Meteorological Service, the New Zealand Institute for Research in Water and Atmosphere, the Australian Bureau of Meteorology, and Meteo-France. Other important institutions include the US National Weather Service and the weather services of all the Pacific Island countries.

As the PI-GCOS Coordinator, the P.M. of this project was an official SPREP delegate to the United National Framework on Climate Change Conventions and organized a PI-GCOS side event for the 10th UNFCCC meeting in Buenas Aires, Argentina in December 2004.

The P.M. is also a member of the WMO Expert Panel on climate instrumentation and a member of the Radio/Internet (i.e. RANET) Steering Group.

How the project is managed in accordance with the 10 Climate Monitoring Principles

- Impact of new systems or changes to existing systems should be assessed prior to implementation

  The 'Instrumentation Project' outlined below will be implemented soon due to the success of a pilot project consisting of the setting up of 10 specially designed tipping bucket rain gauges in various Pacific Island countries. The primary goals of the pilot project were to, not just determine if the instrumentation would stand up to the extreme tropical climate, but also whether the individual Pacific Meteorological service could adequately maintain their networks and delivery data in a timely manner. This has proven to be successful and based on the results of the pilot project we are proposing to expand our efforts under the 'Added Tasks' section of this documents.

- Suitable period of overlap for new and old systems

  The pilot basic instrumentation project has all the instruments co-located with existing similar type instrumentation that been measuring rainfall for many years.

- Site Metadata should be collected and maintained
  All site metadata has been gathered by the respective Pacific Meteorological services.

- Quality Control

  All effort is made by PACRAIN project personnel to conduct the best quality control possible. Summary of our efforts is given is this document.

- Integration into national, regional and global observing priorities

  While most our efforts in this priority are mentioned in section 3) above, all data are available to all researchers either through our web portal or the National Climatic Data Center (NCDC) portal. The PACRAIN data are integrated into several operational satellite rainfall projects and thus, must be updated on a continual basis. An example of a satellite product dependent upon the PACRAIN data base is the NOAA NCEP Climate Prediction Center Merged Analysis of Precipitation product (i.e. CMAP).

- Operation of historically uninterrupted stations and observing systems should be maintained.

  The PACRAIN database contains data back to 1800's from several sites. In addition, we currently support the paper record data rescue efforts that are on going at several Pacific Island Meteorological Services. The Samoan Meteorological Division used PACRAIN support to recently purchase a high quality scanner to preserve their valuable paper data records until they can be properly digitized.

Figure 1. Inside the Samoan Meteorological Service Data Vault

- High priority should be focused on data poor regions

  Given the size and importance of the Pacific Ocean to climate variations and change, the project certainly meets this objective.

- Long term requirements, including appropriate sampling frequencies, should be specified to network designer's operators, etc.

  This has been done with the cooperation of Pacific Meteorological Service personnel.

- The conversion of research observing systems to long-term operations in a carefully planned manner should be promoted.

  While the GCOS program is about climate observing, researchers are discovering that smaller and smaller scale processes contribute to change variability. Thus, while the tipping bucket gauge data will probably be used by the Pacific Meteorological Services at hourly resolution, all tip times are taken and stored and sent to us for research purposes.

- Data management systems that facilitate access, use, and interpret data products should be included as essential elements of climate monitoring systems.

  EVAC maintains a sophisticated data management system with skilled personnel and backups. Please refer to http://pacrain.evac.ou.edu/. Data are regularly sent to other data institutions such as the National Climate Data Center and are included in the Global Historical Climate Network (GHCN).

FY2005 PROGRESS

a) PI-GCOS Basic Instrumentation Project

This section of this document presents the rational and plan for producing a workable, sustainable, and high quality climate, basic instrument measurement network throughout the various Pacific Island Countries (PIC) in accordance with the PI-GCOS Action Plan.

Justification

Developing countries, especially in the Pacific, require information concerning many aspects of their environment to address issues such as enhancing the efficiency of agriculture, water and energy utility management. In addition, the PICs are positioned to take advantage of the high potential in the Pacific for renewable energy projects (solar, wind, etc.). Efficient renewable energy projects could substantially reduce the PICs dependence on imported oil and gas. In addition, the looming specter of global warming will have great impact in the Pacific and the PICs need to monitor changing conditions in order to adapt to them. Data collected and analyzed from the PICs would provide more quantitative evidence of the impact of global climate change in the Pacific to the global community.

However, while most PIC governments generally agree with the issues in the above statement, the role that quality climate networks could play in the successfully addressing the above issues are not completely understood within government circles. Climate networks are required for successful seasonal forecasts, which are possible in the Pacific. The data from these networks initialize and verify these forecasts. Accurate seasonal forecasts help both farmers and utilities by allowing them to optimize power, agricultural and water management.

Issues Involved with Climate Network Establishment

The National Meteorological and Hydrological Services (NMHS) in the Pacific are currently incapable of addressing the issues above. This is due to many reasons, including lack of funding, training, instrumentation and awareness of the services they could potentially supply to the country. While most AID agencies will fund useful workshops on various relevant issues, they are not set up to provide funding for long-term projects, such as the establishment and sustainability of climate networks. Thus, it is incumbent upon the individual PIC governments to provide the needed support. However, the support provided by PIC governments must be at a level they can afford with benefits far outweighing costs. This document represents a plan to do just that. There are three primary issues that must be addressed. They are: 1) professional instrumentation and efficient, cost effective measurement technology and methodology), 2) training and 3) sustainability.

Professional Instrumentation and efficient, cost effective measurement technology and methodology

Given current staffing levels and budgets of most PIC NMHS, it is not feasible to expect a distributed network of PIC NMHS sub-offices within a single country. Without the staff and budget to collect observations, it is of no use to supply instruments to meteorological services who cannot maintain a manual climate network that spans the country in an acceptable manner. What is needed is a network of self-sustaining, high quality, and affordable instruments which produce hourly observations, but can be read (i.e. downloaded into a computer) on a monthly basis. This would free the meteorological staff to conduct the needed climate analyses and work directly with appropriate government and non-government agencies on various projects mentioned above. Thus, with a good climate network in place the services that the NMHS office can supply to the public would be vastly enhanced.

A paradigm which has a high potential for success for the PICs is the use of data loggers with standard instruments that can measure both event and continuous parameters, such as rainfall, wind, relative humidity, etc. A network of instruments, all of the same type, could be standardized and operated with a fairly small staff. Single data loggers are now available which can measure at set resolutions. The cost of such weather-proof data loggers is on the order of $100 each (less if bought in bulk). Monthly visits by meteorological staff would be to download the data directly into laptop computers, clean and re-calibrate the instruments.

The costs of a Pacific wide set of stations would be relatively inexpensive if bought in bulk. The plan has SPREP serving as a central warehouse for bulk storing and repairing equipment.

Training

The advantage of AID agencies is that they are inclined to support workshops and other short-term (3 years) projects. Intermittent funding would go to training PIC climate support staff in site preparation, instrument repair, calibration procedures, and data base management, climate forecasting and interfacing with appropriate agencies for country capacity building. It should be noted that many of the latter type of workshops are already planned or underway under the PI-GCOS umbrella.

Sustainability

Ultimately, climate networks owned by a Pacific country must be supported by that country. Thus, is imperative that the costs are within the limits of the country's capability to afford such a network and that the benefits of a quality, professionally run climate network are fully recognized by the appropriate government agency. It is extremely important that the economic benefits to the country outweigh the costs. Each country in accordance with their requirements would make contributions to a SPREP meteorological instrumentation fund. This would be accomplished under the guidance of the Pacific Island Global Climate Observing System (PI-GCOS) Regional Committee (RC). It should be noted that the RC is composed of a majority of Pacific Island meteorological directors and every country in the Pacific will have to opportunity to be directly represented on the committee on a rotational basis. Spare instruments and parts will be stored at SPREP and sent to PIC NMHS as the need arises. In addition, each meteorological service will keep a few spare parts on hand. A central training and warehouse setup is by far the most cost effective way of assuring standardization and affordability. The costs SPREP incurs with warehouse upkeep, part replacement and shipping would be supported through annual contributions to SPREP by participating island countries after negotiations.

Figure 2. METONE Tipping Bucket Gauge

Figure 3. Installing gauge at the Samoan Meteorological Service

Accomplished Action Items for the Basic Instrumentation Project FY 2005

1. Memorandums of Understanding have been made with most of the Pacific Island meteorological services. The basic tenets of these MOUs are that we will help support their basic instrumentation through PI-GCOS and they will share data.

2. 10 tipping buckets rain gauge sites have been set up in various Pacific countries and we are currently receiving data form these countries.

3. 55 new METONE tipping buckets gauges have been donated by EVAC for an expansion of the PI_GCOS instrumentation project and are currently stored at EVAC along with spare parts and data loggers.

Figure 4. Pilot Project Testbed setup in Niue. The METONE tipping bucket gauge can be seen in between the two manual raingauges

1. Data return has increased in the PACRAIN data by approximately 20% over the last year. This return is due primarily to one on one interaction with each Pacific Island meteorological director.

2. Work has been completed on quality control of the PACRAIN data, although this tends to be an ongoing project.

3. Analysis and Research Highlights

   (a) Initial Scientific Findings

   It has been demonstrated that the METONE tipping bucket gauges tend to overestimate daily rainfall during days of extreme rainfall. Otherwise all three gauges (example shown in Figure 2) measure daily rainfall very closely.

   (b) Products Delivered

   PACRAIN data are continually updated and available for download by anyone. Our web page is constantly being enhanced for ease of use.

b) Progress on the Analysis and Quality of the PACRAIN Data Base

Trends

Understanding changes in climate variability and climate extremes is made difficult by interactions between the changes in the mean and variability. It is well-known that extremes in precipitation have important impacts on vital aspects of environment and our society, including crop yields, power consumption and production, and human health. Thus, as part of our ongoing efforts to use the unique PACRAIN data resources, we have undergone an analysis of not only trends in mean conditions throughout the tropical Pacific, but also an historical analysis of trends in extreme characteristics of precipitation. Table one shows a list of the variables that we have analyzed in our study.

Results show that there are pronounced changes in many of the variables analyzed, and that significant regional patterns also exist. Similar analysis has also been preformed on monthly data, in part to examine the role of the Pacific Decadal Oscillation in explaining some or all of observed trends. However, preliminary results suggest that the identified trends at particular locations are independent of the PDO phase.

Quality Control

Over the past few years the PACRAIN database has undergone a number of upgrades, and this trend continued in FY 2005. Previous upgrades focused on infrastructure, but the most recants improvements have been to the underlying data. The quality control of PACRAIN data is an ongoing process, and errors are corrected as they are discovered. A comparison of PACRAIN records to satellite data was performed in May to evaluate the accuracy of PACRAIN timestamps. The key result of the comparison was that most PACRAIN observations fall within ±6 hours of the corresponding satellite estimates. The comparison also led to discovery of two systematic errors, which have been corrected. Another database improvement was the creation of a new data flag to indicate an estimated timestamp, which has been applied to all relevant records.

In addition to specific database upgrades, other routine activities continued throughout the year. The PACRAIN database continues to be upgraded on a monthly basis with data from the SPaRCE project, NCDC, NIWA, and the island of Niue. For the period October 2004 – September 2005, approximately 85000 new records were added to the database. In January 2005, "Upgrades to and expansion of the Comprehensive Pacific Rainfall Database (PACRAIN)" was presented at the 85th AMS Annual Meeting in San Diego, CA. In September 2005, "Temporal comparison of the Comprehensive Pacific Rainfall Database (PACRAIN) with satellite rainfall estimates" was accepted for presentation at the 86th AMS Annual Meeting in Atlanta, GA. Also, work has begun to expand both of these presentations into journal articles.

Extreme frequency	Frequency of daily rainfall exceeding the 1961–1990 mean 99th percentile
Precipitation days	Frequency of days with at least 2 mm of precipitation
Extreme intensity	Average intensity of events greater than or equal to the 99th percentile each year, i.e. in the four wettest events
Extreme proportion	Percentage of annual total rainfall from events greater than or equal to the 99th percentile, i.e. received in the four wettest events
Heavy precipitation days (absolute threshold)	Number of days (per year/season/month) with precipitation amount >10 mm
Very heavy precipitation days (absolute threshold)	Number of days (per year/season/month) with precipitation amount >10 mm
Highest 1 days precipitation amount (absolute extreme)	Maximum (annual/seasonal/monthly) precipitation sums for 1-day intervals
Consecutive dry days	Greatest number consecutive days precipitation <1mm
Consecutive wet days	Greatest number consecutive days precipitation >1mm

Table 1: Extreme value indicators used in this Study

1. High Resolution XBT/XCTD Transects

Dean Roemmich
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PROJECT SUMMARY

The High Resolution XBT (HRX) network was initiated in 1986 along a transect between New Zealand, Fiji, and Hawaii. It was subsequently expanded during the 1990's to include basin-spanning transects in all of the oceans. Major partners in the HRX network include SIO (Pacific and Indian Ocean), NOAA/AOML (Atlantic), and CSIRO (SW Pacific, Indian). Typically, each transect is repeated on a quarterly basis to resolve variability on annual and longer periods. A technician is usually on board in order to carry out sampling, with XBT probe spacing at 50 km or less in the ocean interior and as fine as 10-15 km in boundary currents. Sparse XCTDs are also deployed on some lines, and technical support is provided for ancillary programs, such as Argo float deployments and installation of VOS/IMET marine meteorological packages. Fig 1 shows the present transects sampled by the SIO HRX program and partners in the Indian and Pacific Oceans.

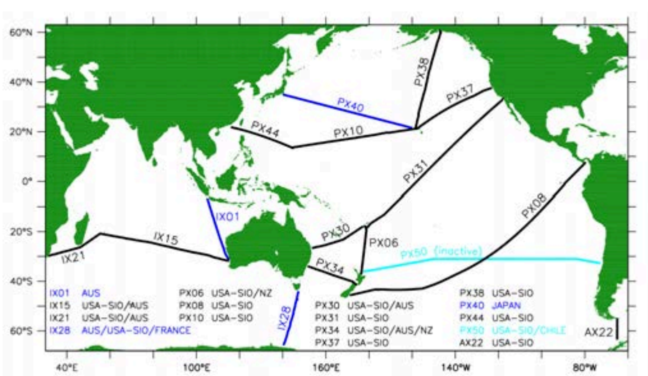

Fig 1: The HRX Network in the Pacific and Indian Ocean. International partnerships are indicated in the notes on the bottom of the figure.

A primary scientific goal of the HRX network is to determine whether interannual variability in the transport of heat by ocean currents is a major contributor to the heat budget of the ocean and hence to air-sea interactions and feedbacks in the climate system. Specific scientific objectives of the HRX program are to:

- Measure the seasonal and interannual fluctuations in the transport of mass, heat, and freshwater across transects which define large enclosed ocean areas.
- Determine the long-term mean, annual cycle and interannual fluctuations of temperature, geostrophic velocity and large-scale ocean circulation in the top 800 m of the ocean.
- Obtain long time-series of temperature and salinity profiles at precisely repeating locations in order to unambiguously separate temporal from spatial variability of properties.
- Determine the space-time statistics of variability of the temperature and geostrophic shear fields.
- Provide appropriate *in situ* data (together with Argo profiling floats, TAO moorings, air-sea flux measurements, sea level etc.) for testing ocean and ocean-atmosphere models.
- Determine the synergy between HRX transects, TOPEX altimetry, Argo, and models of the general circulation. What are the minimal sampling requirements for *in situ* data?
- Identify permanent boundary currents and fronts, describe their persistence and recurrence and their relation to large-scale transports.
- Estimate the significance of baroclinic eddy heat fluxes.

In the context of NOAA's *Program Plan for Building a Sustained Ocean Observing System for Climate*, the HRX Network is a part of the Ship-of-Opportunity Networks. It directly addresses objective 3 of the Plan: *Document the ocean's storage and global transport of heat and fresh water.*

The configuration of the HRX Network is in accordance with the recommendations of the Upper Ocean Thermal Review (Melbourne, 1999, see http://www.brest.ird.fr/soopip/).The SIO HRX network is managed for compatibility with the NOAA/SEAS system, and all XBT casts are transmitted to the GTS in near real-time using SEAS. Technical monitoring of the HRX Network is carried out by the JCOMMOPS SOOP Technical Coordinator (http://jcommops.org/soop) . D Roemmich is a member of the JCOMMOPS Observations Coordination Group as well as the Ship Observations Team. International collaborations are as noted in Fig 1 above. Display of SIO HRX transects and downloadable data are available at the web site http://www-hrx.ucsd.edu . All HRX data are sent to NODC to be archived.

FY2005 PROGRESS

This progress report covers the period October 2004 – September 2005.

Observations

HRX transects were collected along the routes illustrated in Fig 1, and as described in the previous section, in the following months:

- PX37/10/44 (North Pacific - San Francisco to Hawaii to Guam to Hong Kong)
  - 4 transects: November 2004, March 2005, May 2005, July 2005
- PX38 (North Pacific – Hawaii to Alaska)
  - 3 transects: December 2004, May 2005, August 2005
- PX08 (South Pacific – New Zealand to Panama)
  - 3 transects: October 2004, March 2005, September 2005
- PX06/31 (Central Pacific – New Zealand to Fiji to Los Angeles)
  - 4 transects – November 2004, February 2005, May 2005, August 2005
- PX30 (South Pacific – Brisbane to Fiji)
  - 4 transects – December 2004, March 2005, June 2005, September 2005
- IX15/21 (South Indian – Fremantle to Mauritius to Durban)
  - 3 transects - November 2004, February 2005, September 2005

Overall, this represents a data return rate of about 90% (numbered line occupations relative to nominal sampling of four occupations per year). Normally, the data return is close to 100%. See logistics below.

In addition, logistical assistance and/or some XBT probes are provided collaboratively for:

- PX34 (South Pacific – Wellington to Sydney)
- IX28 (Southern Ocean – Hobart to Antarctica)
- AX22 (Southern Ocean - Drake Passage)

Logistics

The commercial shipping industry has undergone enormous change since the beginnings of the HRX network 20 years ago. With respect to HRX sampling, there are two main changes. First, consolidation in the industry has resulted in the elimination of many shipping routes and an increasing reliance on feeder vessels. Second, ships remain on a given line for a much shorter period of time, necessitating frequent recruitment/changeover to new vessels. The specific impacts on HRX sampling are:

1. Elimination of the preferred South Pacific route (PX50) in 2003. The best alternate is PX08.
2. Occasional disappearance of IX15/21, including in early 2005. We have re-initiated sampling in September 2005 using two vessels (including a feeder vessel on IX21).
3. Occasional shifting of the Central Pacific route between the preferred Suva – Honolulu track and the present Suva – Los Angeles track.
4. Sporadic and changing tanker traffic along PX38.

All of these result in increasing demands on the HRX program's operations manager and the staff of trained ship riders, for recruitment and setup of new vessels.

Development

Two substantial development tasks are taking place in the present year.

First, the DOS-based Sippican MK12 data acquisition card has been discontinued and replaced by a completely different (Windows-based MK21) system. We have carried out a major software development to make the SIO automatic XBT launcher system compatible with the MK21 and also compatible with NOAA/SEAS XBT data acquisition. This work was done collaboratively with NOAA/AOML. Concurrent replacement of shipboard computers and acquisition of MK21 cards has also been necessary. The new systems are presently being phased into use along all routes.

A new electronic temperature profiler from Sippican (LMP5-T1), providing research quality data to 2000 m from a 20 knot ship, is presently being tested and evaluated. Such a profiler is badly needed, especially for profiling in the western boundary currents. If testing is successful, our plan is to phase out XCTD sampling as Argo coverage comes on line, and to begin sampling with the LMP5-T1 in selected regions where 2000 m sampling is most beneficial. Part of the evaluation will be a comparison of concurrent depth (fall rate plus single pressure point for calibration) from the LMP5-T1 with depth (fall-rate) from the T-7 XBT.

Analysis and research highlights

HRX data are being incorporated in regional, basin-wide, and global analyses.

- Willis *et al* (2004) estimated global ocean heat content and thermosteric sea level rise for the period 1993 to 2003 using a combination of XBT and satellite altimetric height data.
- One of the regions of the globe with strongest warming in the past decade is the Tasman Sea, where Sutton *et al* (2005) used XBT data from PX34 to determine the vertical structure and magnitude of the decadal warming signal.
- A closed heat budget, on interannual time-scales, for a large ocean area in the southwestern Pacific (PX06, PX30, PX34), was described by Roemmich *et a*l (2005). The interannual variability in air-sea flux, ocean heat flux convergence and air-sea flux in the upper 100 m was balanced to within 6 W/m^2. This is the first study closing the interannual heat balance using subsurface measurements of ocean heat flux convergence.
- Interannual circulation variability in the Northeast Pacific was described by Douglass *et al* (2005) using XBT data from PX37 and PX38 together with a data assimilation model. Principal variability during the decade of observations was an increase in the eastward transport of the North Pacific Current in 1998, with a resultant increase in the subtropical gyre recirculation in the eastern Pacific.

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2. NOAA'S XBT NETWORK

Robert L. Molinari

NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

The primary objective of the AOML XBT component of the ENSO Observing System is to provide oceanographic data needed to initialize the operational seasonal-to-interannual (SI) climate forecasts prepared by NCEP. Specifically, AOML manages a global XBT network that provides subsurface temperature data. The subsurface data are used in the initialization of the SI forecast models and have been shown to be necessary requirements for successful predictions. Global coverage is now required as the forecast models now not only simulate Pacific conditions but global conditions to improve prediction skill. Secondary objectives of this project are to use the resulting data to increase our understanding of the dynamics of SI and decadal time scale variability, to perform model validation studies and to quality control delayed mode data to climate research standards. Thus, this project addresses both operational and scientific goals of NOAA's program for building a sustained ocean observing system for climate.

XBT data provide subsurface temperature data to a depth of approximately 800 meters along 30 selected transects in all three-ocean basins. Data are stored on the computer system on the ships on which we have installed Shipboard Environmental data Acquisition (SEAS) Systems. The real-time data are transmitted via Inmarsat Std. C. Automatic quality control tests are applied to the data and those profiles that pass are distributed on the GTS. An operator reviews those profiles that fail the automatic quality control procedures. The operator decides whether or not to send the data to the GTS. Full resolution data are stored on disks and obtained by ship greeters when the VOS return to port. The data are forwarded to AOML, placed in established formats and then sent to the National Oceanographic Data Center (NODC). Additionally, all Atlantic XBT data are scientifically quality controlled at AOML as NOAA's contribution to the GTSPP. These data are stored at the Atlantic Data Assembly Center located at AOML and returned to and archived at NODC after review.

XBT data are used in real time for ENSO monitoring and prediction and the initialization of climate models at centers for environmental prediction and in delayed mode for research concern seasonal to decadal climate studies of the upper ocean thermal layer. There are no restrictions on sharing this information as it is distributed in real time on the GTS.

Addressing NOAA's Program Plan

This project provides critical data for initializing SI forecasts. The data resulting from this project will also address objectives 3 and 4 (i.e., the heat content and air-sea flux elements) of the OCO Program Plan.

Management in Cooperation with International Panels

The AOML Voluntary Observing Ship (VOS) XBT Program is a participating member of JCOMM and JCOMMOPS. The AOML VOS XBT program is represented annually at the WMO/IOC Ship Observations Team (SOT) meeting and Steven Cook presently is Chair of the Ship of Opportunity Implementation Panel (SOOPIP), a JCOMMOPS subcommittee. Participation on these international panels provides an important mechanism for integrating and coordinating with other national or regional programs which, in the long run, improves our national climate mission by making more efficient and effective use of available resources.

Responsible institutions

The VOS XBT program is a component of the GOOS Center located within the Physical Oceanography Division of AOML and manages NOAA's Voluntary Observing Ship (VOS) XBT Program. The VOS XBT Program utilizes the National Weather Service Global Telecommunications System (NWSGTS) gateway for the real-time distribution of data and the National Oceanographic Data Center (NODC) for the archival of delayed mode data.

Interagency and international partnerships

The GOOS Center has close cooperative working arrangements across all NOAA Line Offices (NWS, NESDIS, NOS, NMFS and OMAO), the U.S. Navy and Coast Guard, several major national (SIO, WHOI, RSMAS, URI, UW and SCMI) and international (BSH, CSIRO, BOM, SABOM, JAMSTEC, IFREMER, IRD-Brest and IRD-Noumea) oceanographic and meteorological institutions as well as private contractors. For example, the program provides XBT's to international partners for deployment on lines of mutual interest. The partners provide all the ship greeting and data transmission functions, which reduces considerably the logistical load on the GOOS Center and in many instances provides data in regions that otherwise would not be accessible to us.

FY 2005 PROGRESS

Instrument/platform acquisitions for the fiscal year and where equipment was deployed

XBT's are deployed along selected transects in cooperation with the international group overseeing VOS operations (SOOPIP) in the Pacific, Atlantic and Indian Oceans. In addition, 6140 probes were supplied to international partners primarily for deployment in the western tropical Pacific and tropical Atlantic Oceans. Deployments during FY2005 are shown in Figure 1.

Number of AOML deployments by calendar year – compare to the previous year.

2004: 15,811
2005: 14,290

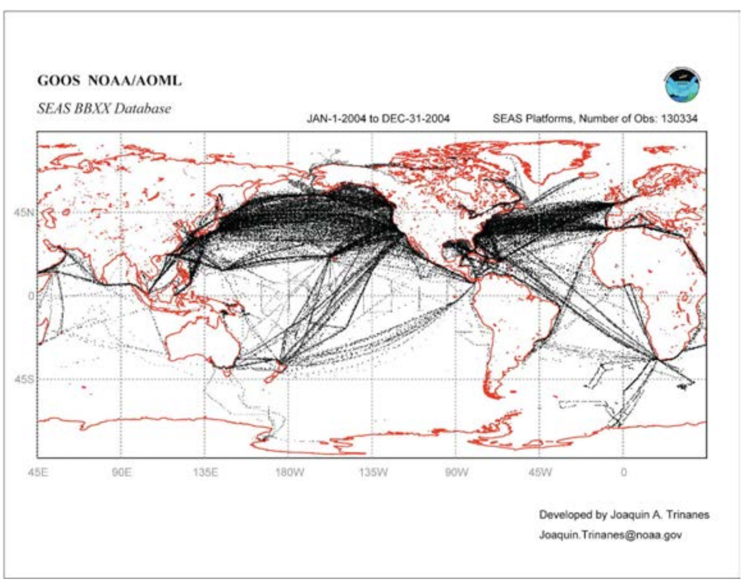

Figure 1. XBT Deployments during FY 2005.

Percentage of data return for fiscal year

The ratio of XBT's deployed to real time data transmitted is essentially 100% except for profiles from High Density transects. Not every High Density XBT collected is transmitted in real time primarily due to time limitations while sampling, but all delayed mode data not transmitted in real time are still inserted onto the GTS within 30 days of the completion of each cruise. Probe failure remains consistently between 2 % and 5 % with greater higher failure rates in the higher latitudes during the hemispheric winters.

Where the data are archived

All XBT data are archived at the NODC and a subset of all Atlantic XBT data are archived at a DAC located at AOML.

Anticipated and unanticipated project costs

The cost per probe will increase $1.82 to $33.82 during FY06. The purchase of replacement equipment will be reduced to allow for the purchase of the same number of probes during FY06.

Problems encountered

Volatile shipping industry requires considerable time and travel resources to continually recruit and re-outfit vessels for participation in the VOS. This volatility is particularly troublesome in the Indian Ocean, where we have not been able to maintain a portion of the low-density network.

Late funding has precipitated an increase of air shipping vs. ground shipping to deliver on time XBT's to those participating Research and Voluntary Observing Ships that had pre-set time schedules.

Logistical considerations

This section is not applicable to this activity.

Research highlights

Continued interactions with international scientists have demonstrated the importance of continued XBT sampling in the tropical Atlantic. Specifically, AOML scientists are involved in planning of the African Monsoon Multidisciplinary Analysis project. The objectives of AMMA are to study the West African monsoon and it is associated offshore features (i.e., the atmospheric waves that can generate tropical storms and hurricanes).

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3. Atlantic High Density XBT Lines

Molly O. Baringer, Gustavo J. Goni, and Silvia L. Garzoli

NOAA/Atlantic Oceanographic and Meteorological Laboratory

PROJECT SUMMARY

This program is designed to measure the upper ocean thermal structure in key regions of the Atlantic Ocean (Figure 1). The seasonal to interannual variability in upper ocean heat content and transport is monitored to understand how the ocean responds to changes in atmospheric and oceanic conditions and how the ocean response may feedback to the important climate fluctuations such as the North Atlantic Oscillation (NAO). This increased understanding is crucial to improving climate prediction models. Within this context, five XBT lines have been chosen to monitor properties in the upper layers of the Atlantic Ocean. The continuation of AX07 and AX10 and the implementation of AX08 and AX18 were recommended at the Meeting of the Ocean Observing System for Climate held in St. Raphael in 1999.

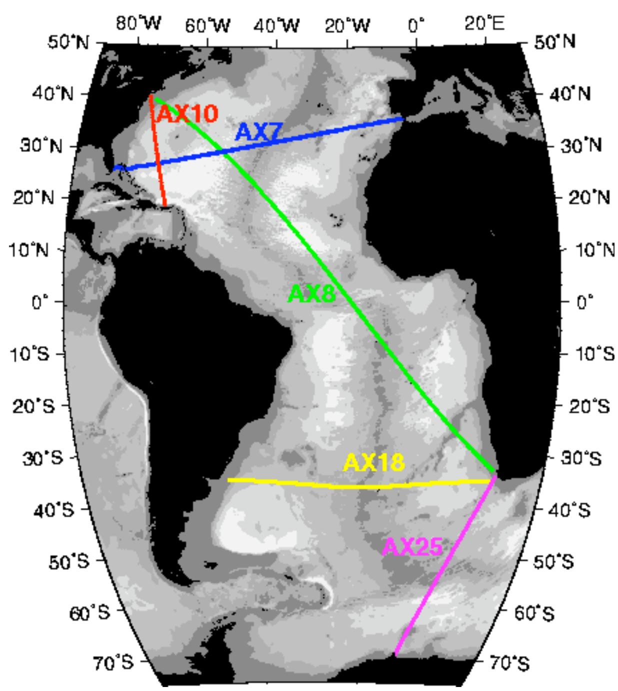

Figure 1. Location of the five high density XBT lines (AX07, AX08, AX10, AX18, and AX25) maintained by NOAA/AOML.

The high-density line AX07 is located nominally along 30°N extending from the Straits of Gibraltar in the eastern Atlantic to the east coast of the United States at Miami, Florida. This latitude is ideal for monitoring heat flux variability in the Atlantic because it lies near the center of the subtropical gyre, which has been shown to be the latitude of the maximum poleward heat flux in the Atlantic Ocean.

The high-density line AX10 is located between New York City and Puerto Rico. This line closes off the United States eastern seaboard, where subtropical temperature anomalies could have the greatest interaction with the atmosphere. This line was chosen to monitor the location of the Gulf Stream and its link to the NAO.

The high-density line AX08, part of the Tropical Atlantic Observing System, crosses the tropical Atlantic in a NW-SE direction between North America and South Africa. Historical data along AX08 and other historical temperature observations in the tropics exhibit decadal and multi-decadal signals. It has been hypothesized that this large time scale signal may cause atmospheric variability. Given the importance of the tropical Atlantic in climate variability, and the scarcity of observations in this region, data obtained from the measurements along this line are key to improving our understanding of the ocean and our ability to forecast climate. Temperature profiles obtained from this line will help to monitor the main zonal (east-west) currents and undercurrents in the tropical Atlantic and to investigate their spatial and temporal variability.

The high-density XBT line AX18, which runs between Cape Town and South America (Montevideo, Uruguay, or Buenos Aires, Argentina) is geared towards improving the current climate observing system in the South Atlantic, a region of poor data coverage. The main objective of this line is to monitor the meridional mass and heat transport in the upper 800 m across 30°S. Given the importance of the South Atlantic and the scarcity of observations in this region, data obtained from the measurements along this line will be used to investigate the role of the South Atlantic in improving climate forecasts.

The AX25 line was implemented to measure changes in the variability in the upper layer interocean exchanges between South Africa and Antarctica on seasonal and interannual time scales. In addition, by exploiting the relationship between upper ocean temperature and dynamic height, XBTs can be used to infer velocities even in the Southern Ocean where salinity changes are important. In this way XBT sections can be used to measure changes in oceanic heat transport.

The global atmospheric and oceanic data from Ships of Opportunity (SOOP) have been the foundation for understanding long-term changes in marine climate. This program is a direct component of NOAA's Program Plan for building a sustained Ocean Observing System for Climate and directly addresses one of its *milestones:*

- Occupy 41 volunteer observing ship (VOS) lines for high accuracy upper ocean and surface meteorological observations, by 2007 (Figure 2).

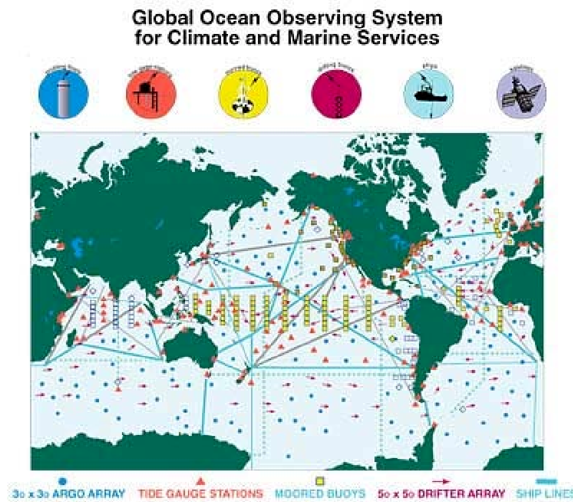

Figure 2. NOAA's Global Observing System for Climate.

The Global Ocean Observing System (GOOS) Center and its integral components, the Global Drifter Program (GDP) and Voluntary Observing Ship (VOS) XBT Program are both participating members of JCOMM and JCOMMOPS. The VOS XBT program is represented annually at the WMO/IOC Ship Observations Team (SOT) meeting. AOML presently Chair the Ship of Opportunity Implementation Panel (SOOPIP).

Responsible institutions

NOAA/AOML is responsible for managing all aspects of this project.

Interagency and international partnerships

Several agencies are currently collaborating with this project. The Argentine Hydrographic Naval Office (SHN) provides the personnel to deploy the XBTs on AX18; the University of Cape Town provides for the deployments along AX08 and AX25. The South African Weather Service is our contact in Cape Town and Durban to store the equipment in between transects and to provide ship riders.

Relation to the Ten Climate Monitoring Principles

High-density line AX07 and AX10 have been maintained since 1994 and 1996, respectively, providing a homogeneous data set for almost a decade. Sustained observations from these and the other three high-density lines are required to have observations with adequate spatial and temporal resolution for climate studies. High-density observations in AX08, AX18, and AX25 provide data in poorly surveyed regions. Data are easy to access, interpretation and visualization. AOML has the facilities, personnel and infrastructure to maintain a stable, long-term commitment to these observations.

FY 2005 PROGRESS

Instrument/platform acquisitions for FY2005 and locations where XBTs were deployed

Line	Number XBTs launched
AX07	720
AX08	1100
AX10	440[(1)]
AX18	720
AX25	260

[(1)] Does not include an underway (September 2005) transect.

The exact locations of XBT deployments are shown on the web page corresponding to each line (Figure 3).

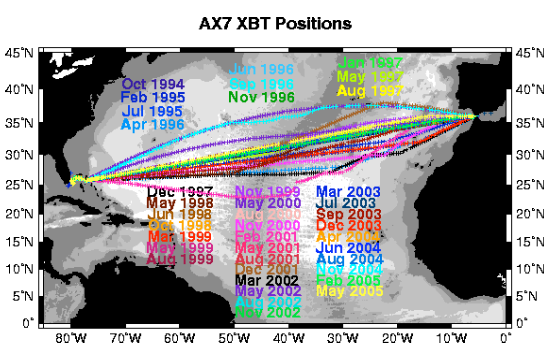

Figure 3. Locations of XBT deployments.

4. Observations of Air-Sea Fluxes and the Surface of the Ocean – Atlantic and Pacific VOS

Robert A. Weller, Frank Bahr, David S. Hosom
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PROJECT SUMMARY

Central to present efforts to improve the predictability of climate is the need to understand the physics of how the atmosphere and ocean exchange heat, freshwater, and momentum and, in turn, to accurately represent that understanding in the models to be used to make predictions. At present, over much of the globe, our quantitative maps of these air-sea exchanges, derived either from ship reports, numerical model analyses or satellites, have errors that are large compared to the size of climatically significant signals. Observations made using the IMET technology on the Volunteer Observing Ships on long routes that span the ocean basins are essential to providing the accurate, in-situ observations needed to:

1. identify errors in existing climatological, model-based, and remotely-sensed surface meteorological and air-sea flux fields,
2. provide the motivation for improvements to existing parameterizations and algorithms,
3. provide the data needed to correct existing climatologies, and
4. validate new model codes and remote sensing methods.

AutoIMET was developed by the Woods Hole Oceanographic Institution to meet the need for improved marine weather and climate forecasting. It is a wireless, climate quality, high time resolution system for making systematic upper ocean and atmospheric measurements. This interfaces to the NOAA SEAS 2000 (Shipboard Environmental (Data) Acquisition System) that automatically receives meteorological data (from the AutoIMET) and sends in automated one hour satellite reports via Inmarsat C.

This system documents heat uptake, transport, and release by the ocean as well as the air-sea exchange of water and the ocean's overturning circulation.

The CORCIII program now supports two ships in the Pacific and one ship in the Atlantic. A second Atlantic ship is being selected to replace the Sealand Express, which is now out of service.

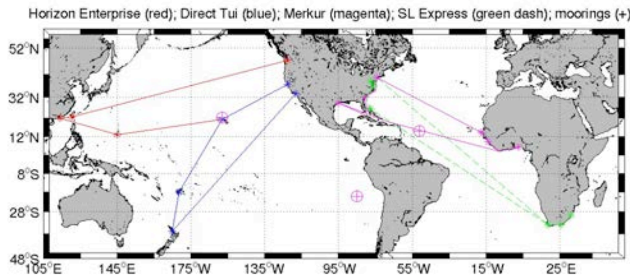

Figure 1. Route Map. Note the Ocean Monitoring Stations (circle with cross) being operated by WHOI. The Horizon Enterprise is shown in red. The Direct Tui (replaced the Columbus Florida) is shown in blue. The M/V Merkur is shown in magenta. The Sealand Express route is open and waiting on a new ship assignment.

Descriptions, technical information and data from the several VOS being serviced is posted on the site: http://uop.whoi.edu/vos/ Data (plots) are available for all ship sets. Data (numbers) are available via anonymous ftp for the last data set only: ftp.whoi.edu/pub/users/fbahr/VOS. If data from previous times are desired please contact Frank Bahr at: fbahr@whoi.edu. There is a link to the site: http://frodo.whoi.edu where there is detailed information on the AutoIMET and ASIMET modules. Instrument design questions can be addressed to Dave Hosom at: dhosom@whoi.edu

Ship selection and interface to the NOAA SEAS system is via AOML. There is ongoing cooperation with Scripps via the CORCIII program on ship scheduling as well as Southampton Oceanography Centre (SOC) of Southampton UK on Computer Flow Dynamics (CFD) for evaluation of the flow turbulence around the ship and its effect on the sensor placement. Some logistical support is provided by the Southern California Marine Institute on ship turnarounds. There is ongoing cooperation with the Atlantic Marine Ocean and Atmosphere Laboratory (AOML) in Miami on the Atlantic VOS program. There is also ongoing cooperation with many sensor manufacturers and the VOS people at the German Weather Service (Deutscher Wetter Dienst) in Hamburg Germany.

FY 2005 PROGRESS

The CORCIII program now supports two ships in the

Horizon Enterprise.

Direct Tui

M/V Merkur

SeaLand Express (Off line – replacement ship in work)

Pacific and one in the Atlantic. A second Atlantic ship will replace the Sealand Express now out of service.

The following events are for the period 1 July 2004 through 30 September 2005 on a program to improve the surface meteorological and sea surface temperature observations made by U.S.VOS as described by WHOI Proposal Serial No. PO10731.01. The actual accomplishments at this point in time match the goals and objectives of the proposal. During this period we continued to build the program to attempt to improve the observations made by the U.S. Volunteer Observing Ship (VOS) fleet and to collaborate with VOS Expendable Bathythermograph (XBT) investigators on testing and evaluating data from modules developed during the program.

August 2004. The wind sensor encoder on the Sealand Express failed and was replaced when the ship was in Baltimore, MD. Encoder failures seem to be due to overvoltage from the power supply coupled with ship power surges.

Sept 2004. Turnaround of AutoIMET on the Horizon Enterprise in Oakland, CA. The ship has provided a bulkhead fitting that will permit the SST to operate on a.c. power and remove the batteries and acoustic modem (HullCom). This improves reliability, gives SST every 6 minutes to SEAS, and reduces the cost of operation (no batteries).

October 2004. The system was turned around in Baltimore MD. The data will be processed and be available on the web. The in port time was very short and the SST could not be serviced since there was welding in the hold that the SST is located in. A SST replacement is planned when the ship returns to Baltimore. The existing batteries should maintain SEAS data from the SST through December 2004 and the SST logger will continue until May 2005 even without battery changes.

November 2004. The SST on the Sealand Express was replaced (since it could not be done in October).

December 2004. Turnaround of the Columbus Florida in Long Beach CA.

March 2005. The Horizon Enterprise is scheduled for maintenance in a shipyard and all of the sensors and cables were removed since repairs were planned in the areas that these sensors and cables were in.

February 2005. We learn on short notice that the SeaLand Express has been sold and will change routes. The system was removed and returned to WHOI.
A replacement ship is being sought for the Cape Town to New York track.

March 2005. On short notice, we learn that the Columbus Florida is relocating from the Pacific to a new route in the western Atlantic. All of the AutoIMET and SEAS equipment were removed from the ship.

April 2005. Visit Newark N.J. to see candidate ship M.V.Merkur.

May 2005. The AutoIMET and SEAS systems were re-installed on the Horizon Enterprise in Oakland CA. Parts of the superstructure in the bow were changed and we lost our cable feed-throughs that provide power and SST data. The Captain was able to have feed-throughs installed and the installation was completed. The SEAS system was also re-installed.

May 2005. Visit M/V Merkur in Houston TX to prep for an AutoIMET installation.

June 2005. The Enterprise wind sensor had a problem and was replaced in Oakland CA.

June 2005. Visit Direct Tui in Los Angeles to install radio link in prep for AutoIMET installation.

July 2005. AutoIMET installation on the M/V Merkur in Newark N.J. Not completed due to very short port stop. Heavy work was comleted.

August 2005. AutoIMET installation on the Direct Tui in Los Angeles CA.

August 2005. Repair wind and SST sensor on Horizon Enterprise. Installed battery for wind and SST to insure isolation from ship power surges.

September 2005. Complete installation on the M/V Merkur in Houston TX. Two sensors had problems wind and SST. Followed ship to Savannah GA and was able to fix wind sensor but not SST. Will meet ship on next cycle to fix SST.

The CFD (Computer Flow Dynamics) work continues at Southampton Oceanography Centre on the feasibility of CFD on generic VOS.

5. Developing an Underway CTD

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PROJECT SUMMARY

The objectives of the Consortium on the Ocean's Role in Climate (CORC) include maintaining developmental elements of the ocean climate observing system.

New observational techniques being developed include an underway CTD that operates like an expendable XBT or XCTD, except that at the end of descent the probe is recovered using the deployment line and then data is transferred from the probe once it is on deck. It is believed that the high quality of observation that instrument retrieval permits will make this instrument attractive for near surface observations of temperature and salinity from vessels that otherwise would use less accurate and more expensive expendables or would not take physical observations at all.

FY 2005 PROGRESS

All of the components of the Underway Conductivity, Temperature and Depth probe (UCTD) system have been designed, built, and used successfully. A description of the components follows. The probe has a (Precision Measurement Engineering) four-electrode conductivity sensor, a Thermometrics thermistor, and a (Druck) pressure sensor. Data from the sensors are logged at a frequency of 10 Hz by a Persistor microprocessor to solid state memory. Between UCTD casts, data is downloaded to a laptop computer via a serial connection, the probe's battery is recharged, and the probe is initialized for the next cast. Deck gear consists of a davit, a winch, and a mechanism to rewind line onto the tail. The davit has a 4'x4' footprint, and can pivot and extend. The winch is a Penn International fishing reel equipped with an adjustable speed DC motor for fast and convenient recovery. The rewinding mechanism is driven by a variable speed motor, while level winding is accomplished with an adjustable pitch, reversing unit available commercially.

UCTD operation is carried out easily and safely on an underway vessel, making no demands on vessel operators other than space on an aft quarter to put the equipment. The UCTD is deployed by dropping over the stern while letting the winch free spool. As the fall rate is approximately 5 m/s, a 400-m profile takes 80 s and, assuming the ship is steaming at a speed of 5 m/s (10 knots), 400 m of line is pulled off the winch. The total of 800 m of line deployed at the conclusion of a profile takes roughly 15 min to recover with our current winch design. Rewinding the tail and downloading data take about 10 minutes so that consecutive profiles can be done as rapidly as every 30 min.

The past year saw the UCTD deployed on three cruises. A cruise in September-October 2004, as part of the ONR-sponsored North Pacific Acoustics Laboratory, included the first UCTD deployments by a team that did not include anybody involved in UCTD development. In addition to gathering valuable scientific data on sound speed, this cruise provided a test of UCTD by typical users. The results were encouraging as over 170 casts were completed with only one lost probe. At this loss rate, UCTD cost per cast will be comparable to that of XBTs. Results were reported at the Fall AGU meeting.

A second cruise in January 2005 was a test of UCTD on the NOAA R/V David Starr Jordan. The cruise allowed Valerie Andreassi and her group to evaluate UCTD for possible use by SW Fisheries. Andreassi extensively documented UCTD operation through photos and videos, and briefed others at SWFC on the system.

Several UCTD casts were performed on a third cruise in March/April 2005 as part of the ONR NPAL program. UCTD has proved to be a valuable tool to measure sound speed.

Work has begun to commercialize the UCTD. Talks are ongoing with two oceanographic instrumentation firms, with one commercial prototype probe already designed and tested. At this point, a successful transition of technology seems likely.

1. The Argo Project - Global Ocean Observations for Understanding and Prediction of Climate Variability[5]

Report for Calendar Year 2005

Dean H. Roemmich[1], Russ E. Davis[1], Stephen C. Riser[2], W. Brechner Owens[3], Robert L. Molinari[4], Silvia L. Garzoli[4], Gregory C. Johnson[5]
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Long-Term Goals

The U.S. component of the international Argo Project (http://www.argo.ucsd.edu) is implemented through this award. The present report covers Year 4 of the 5-year project, and builds on progress made by previous awards (Phases 1 and 2) for pilot float arrays and data system development.

By the end of 2006 or early 2007, Argo will have deployed a global array of 3000 profiling CTD floats (Roemmich and Owens, 2000, Roemmich et al, 2002, Gould, 2004), and established a data system to meet the needs of both operational and scientific users for data delivery in real time and delayed mode. The Argo array will provide unprecedented views of the evolving physical state of the ocean. It will reveal the physical processes that balance the large-scale heat and freshwater budgets of the ocean and will provide a crucial dataset for initialization of and assimilation in seasonal-to-decadal forecast models. Argo is a major initiative in oceanography, with research and operational objectives, providing a global dataset for climate science and other applications. It is a pilot project of the Global Ocean Observing System.

Objectives

Phase 1 (9/99 – 9/02) and Phase 2 (7/00 – 6/02) of US Argo provided a total of 187 CTD profiling floats in the Pacific, Atlantic and Indian Oceans. Objectives were to demonstrate technological capabilities for fabrication and for deployment of float arrays in remote ocean locations (Phase 1) and to demonstrate the capability for manufacture and deployment of large float arrays (Phase 2). Technological developments in profiling floats were also implemented, including new generation salinity sensors, improved depth capability, and deployment techniques using fast ships and aircraft. Development of the U.S. Argo Data System was part of Phase 1, on a collaborative basis with international partners. Objectives are to make all Argo data publicly available within a day of collection, applying automated quality control procedures consistent with international Argo practices. Data appropriate for research applications and for comparison with climate change models are not available for several months since they need quality control by salinity experts and evaluation of data over many (10 day) float cycles. Phase 3 is a 5-year project (8/01 – 6/06) including full implementation of the US component of Argo. This report includes Phase 3/Year 4, which as of early December 2005 had deployed 450 CTD profiling floats during CY2005 with a deployment cruise underway at the time of this writing plus support for these deployments, data management activities and for national and international coordination of Argo. Developments in 2005 included deployment of the first operational floats employing Iridium telecommunications; deployment of 22 floats equipped with oxygen sensors; and the implementation of a new controller for profiling floats which will allow for incorporation of these and other, new technologies. Float deployments targeted the Atlantic, Pacific, Indian, and Southern Oceans. Priorities for US float deployment are set by the US Argo Advisory Panel.

Approach And Work Plan

Float production and float deployment has been accomplished by four facilities – SIO (D. Roemmich and R. Davis - float production and deployment), WHOI (W.B. Owens – float production)/AOML (S. Garzoli – float deployment), UW (S. Riser – preparation and deployment of commercially manufactured floats), and PMEL (G. Johnson – deployment of commercially manufactured floats). This distributed effort has been designed to safeguard the US contribution to the Argo project

[5] The ARGO project is managed separately under the National Oceanographic Partnership Program

from unforeseen problems at any one component institution. It also makes Argo success independent of the participation of any individual PI and institution or of any single float design. It allows the large amount of effort to be shared. It encourages individual, technical innovation and enhancement. While the initial focus has needed to be on improving float performance, attention of the PIs will increasingly focus on exploiting the scientific value of Argo. The data system is also distributed, but by function rather than for load-sharing. AOML (R Molinari) is the national Argo data center, responsible for acquiring the float data received by satellite communications, for carrying out real-time quality control, and for distribution of data via the GTS and to the Global Argo Data Assembly Centers. The second step in data management is a semi-automated recalibration of the salinity sensor carried out by PMEL (G. Johnson), using a high quality temperature/salinity climatology for comparison with float temperature/salinity data (Wong et al, 2003). The final step is individual examination of all profiles by the float-providing PIs, in order to provide high-quality data suitable for research applications. US Argo PIs are involved in all of these components.

All Argo data are freely available within about 24 hours of collection, and can be accessed from the GTS or internet (http://www.usgodae.org/, or http://www.ifremer.fr/coriolis/cdc/argo.htm).

Work Completed

It was reported in 2002 that, based on the performance of the pilot arrays deployed in Phases 1 and 2, design and production problems were detected in both SOLO and APEX floats that led to shortened instrument lifetimes. Extensive technical analysis and redesign was carried out over the first 9 months of 2002, leading to substantial improvements in float pumping and control subsystems. Large-scale float deployments were resumed in the 4th quarter, and by year's end about 1/3 of the Phase 3/Year 1 floats were deployed. Deployment of these modified designs have continued with promising results.

Deployment of the remaining Year 1 instruments plus most Year 2 instruments was completed in 2003. A significant disruption was caused by a recall of salinity sensors by SBE in August 2003. A problem associated with the pressure sensor had been detected by S. Riser at UW. Riser worked with the manufacturer to identify the fault. This resulted in the recall and a hiatus in the deployment of floats with SBE sensors that effectively lasted to the end of 2003.

There is enough data on the redesigned floats to confirm that significant improvements have occurred in float lifetimes, much of that due to the technical and engineering efforts of the U.S. partners. Figure 1 is a composite of the failure rates of all of the floats in the international program. The Argo program plan has a goal of a 10% failure rate over four years (146 cycles). Floats deployed in 2005 have not been deployed for a large number of cycles but these early results indicate that the U.S. float reliability has improved as a result of these technical improvements and may be approaching the goal of 10% failures over four years.

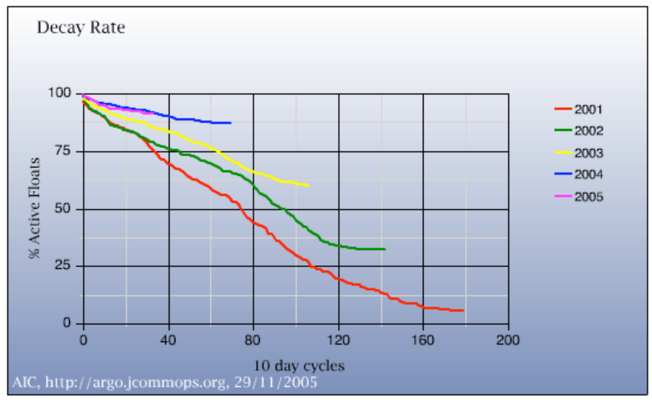


Figure 1. Float Reliability

All Argo profiles are now subjected to the internationally-agreed automated quality control procedures and are distributed via the GTS. The US Argo Data Center (AOML) provides all US data to the Global Argo Data Assembly Centers (GDACs) in Monterey, California and Brest, France in standardized Argo NetCDF format. The US delayed-mode data center (PMEL) provides suggested salinity recalibration information for US floats and has led the development of procedures that were endorsed by the Argo Science Team in March 2003 for incorporating delayed-mode quality control in the standard data files. The delayed-mode quality control procedures are now being implemented operationally on all U.S. profiles. After PI examination, the delayed-mode salinity data will be distributed by the U.S. Argo Data Center.

The US GDAC serves the global collection of Argo profiles through OPeNDAP servers, and Live Access Server from NOAA/PMEL. These servers integrate Argo data into the National Virtual Ocean Data System (NVODS), and the International Ocean Observing System Data Management and Communications (IOOS/DMAC) scheme.

The U.S. Program plays a strong role on the international Argo Data Management Team. Mark Ignaszewski (FNMOC) is now ADT co-chair. The PMEL technique for salinity recalibration has been distributed to international partners, along with assistance in getting it running, and it has been adopted internationally. AOML, participating on the ADMT, provides input to methodology development and leads efforts in product evolution. Finally, in the data management realm, AOML has provided assistance to other groups (e.g., China, South Korea and India) as they establish their real-time data management procedures.

Data management methodology is not static. Both AOML and PMEL continue to implement changes in the procedures required by the international Argo Data Management Team.

The US is the technology leader in profiling floats, and our technical improvements have been shared with international partners. 85% of all of the present Argo array is made up of floats manufactured in the USA.

The consortium plays strong leadership roles in the international Argo project. In the past year this support has included the employment of Dr. John Gould as Argo Director, working closely with Dr. Dean Roemmich (Argo Science Team Chairman). US consortium members provide coordination for deployment planning in the Pacific, Atlantic, and Southern Oceans.

Results

The international Argo array now includes over 2200 floats (Figure 2, from http://argo.jcommops.org) compared with 1572 active floats a year earlier. This represents slightly more than two-thirds of the 3000 float array planned for completion by the end of 2006. Float deployments increased dramatically in the past two years, especially in the remote sparsely sampled regions. Much of this was due to collaborations with the National Institute of Water and Atmospheric Research in New Zealand using the research vessel KAHAROA. AOML partnerships with Brazil, Argentina and South Africa will provide deployment opportunities in the South Atlantic Ocean in 2006 and the links with NIWA will continue enabling continued coverage of the remote and logistically difficult South Pacific.

The northern hemisphere bias of the array has, basically, disappeared with 52% of the active floats now in the southern hemisphere. Data are being used by at least 12 operational centers worldwide, and by a broad community of researchers. The Argo Data Management System is operating, delivering profiles in near real-time to operational and other users via the GTS and the internet. The ability to produce scientific-quality data has been demonstrated and is starting to be implemented for all floats with public internet distribution.

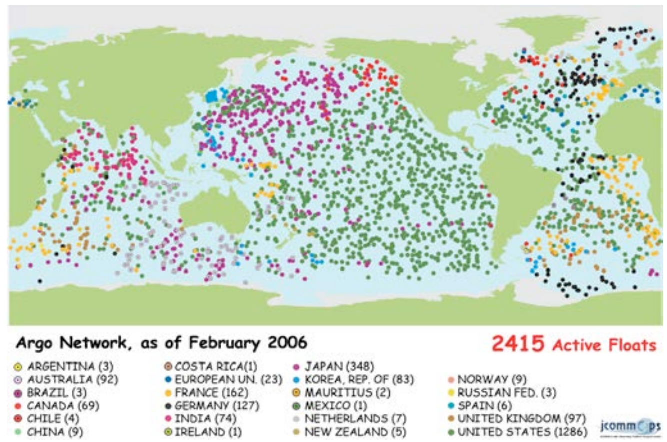
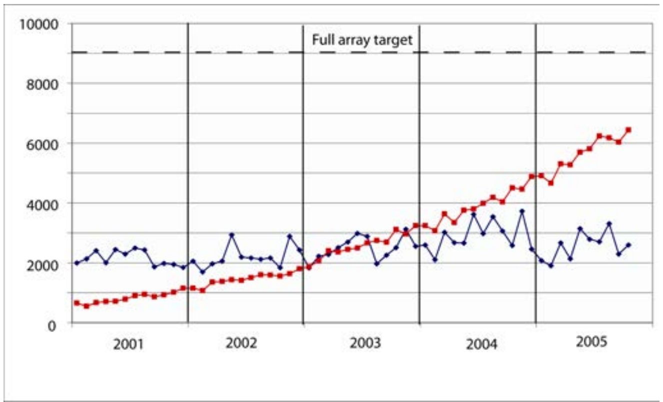


Figure 2. The Argo Array as of 30 November 2005 (US floats in Green)

Although the Argo Project is still young it has made possible a wide range of operational and research applications of Argo and pre-Argo profiling float data. This was clearly demonstrated at the First Argo Science Workshop held in Tokyo in November 2003 and co-sponsored by NOAA. There were 85 oral and poster presentations on topics ranging from the air-sea interaction below tropical cyclones, monsoonal and ENSO effects, seasonal mode water production, investigation of basin-scale ocean currents, global ocean heat and fresh water storage and the detection and attribution of climate change.
These presentations can be accessed at http://www.argo.ucsd.edu/. US PIs are conducting research in all of these areas and there is increasing use of Argo data in operational centers. The PI-led research is reflected in the attached bibliography.

The second international science workshop is planned for March 2006, in conjunction with the Ocean Surface Topography Science Team workshop in Venice, Italy. One hundred abstracts from 16 nations were submitted specifically for the Argo Workshop.

It is clear that Argo's contributions to the ocean observing system – including observations of subsurface salinity and extensive coverage of remote ocean areas – are a profound increment in our ability to characterize water masses and large-scale circulation, (Figure 3) and to make accurate estimates of heat and freshwater storage and their transport by ocean currents..



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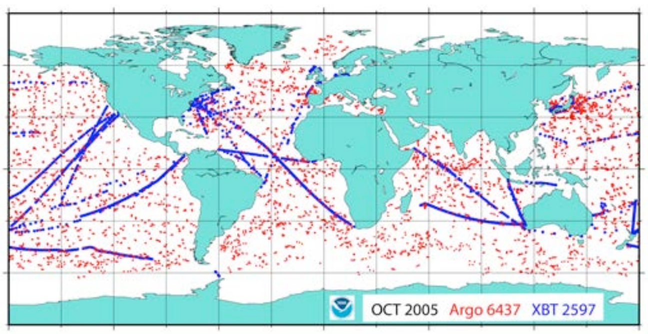

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Figure 3. (A) Argo and XBT Near Real-Time Profiles Per Month; (B) Data Delivered in Real Time during October 2005 from Argo (6437 Profiles Typically to Over 1000m - Red Dots) and from the High density XBT Network (Temperature Only to Typically 750m – Blue Dots). Courtesy AOML.

The quasi-random distribution of Argo data compared with data provided by ships is demonstrated in Figure 3B. Argo's uniform distribution provides the ideal complement to satellite altimetry data (Willis et al, 2003) so as to address the issues of global heat and fresh water storage and sea level rise and for data assimilation into global models.

Impacts, Applications, And Transitions

National Security. The US Navy has a strong interest in accurate estimates and forecasts of the physical state of the ocean and the coupled air-sea system, because of the obvious impacts of wind, waves, currents, and temperature on virtually all aspects of naval operations. The Navy has experimental ocean state estimation and forecasting efforts, using both regional and global models, for which Argo provides a central contribution for ocean data assimilation. The Navy interest is further expressed by the hosting of one of the two Global Argo Data Centers (at FNMOC, Monterey), by NAVOCEANO participation as a provider of floats for international Argo, and by NAVOCEANO participation in air deployment of Argo floats. Phase 1 of US Argo was supported by ONR.

Economic Development. The Global Ocean Data Assimilation Experiment (GODAE) has identified a number of applications with substantial economic impacts arising from ocean observations, including improved seasonal-to-interannual (S-I) forecasting, state estimation (now-casting), and coupled physical/biological modeling (e.g., for fisheries). The El NiZo/Southern Oscillation (ENSO) Observing System in the tropical Pacific has demonstrated over the past decade that economic gains in energy, agriculture, and insurance sectors are possible from successful seasonal forecasts. Improvement in S-I forecasting is expected as the tropical observing system is extended and expanded to global coverage, and Argo plays a key role in that expansion.

Quality of Life. Argo is central to an unprecedented capability for global assessment of the evolving climate state of the ocean. The thermal structure of the upper ocean controls the temperature of the lower atmosphere, and is the primary variable defining the physical environment of ocean ecosystems. Over 90% of the increased heat content due to global warming of the air/sea/ice climate system in the past 40 years occurred in the oceans. Climate stresses on ocean ecosystems have serious consequences, and sometimes dramatic ones, such as coral reef bleaching. In the future, the impacts of a varying climate on the health of the seas and coastal ecosystems will become an increasingly important aspect of resource management. The unique niche of the Argo array is to provide global broadscale observations of the upper ocean.

Science Education. Although the Argo project is still very new, it is proving to be an attractive educational asset for secondary, tertiary, and post-graduate levels. For secondary education, the web-based and real-time nature of the Argo data system, as well as Argo's strong climate-relevance, have been keys to engaging student interest in the oceans. Our consortium participates in a UNESCO and IOC-sponsored initiative called SEREAD, (http://argo.jcommops.org/), that uses Argo data in existing secondary science curricula in

Pacific Island countries. In post-graduate education, Argo is already providing primary data for dissertation research of graduate students in the U.S. and other countries.

Related Projects

GODAE: The Global Ocean Data Assimilation Experiment uses satellite and in situ ocean datasets in data assimilation models for practical applications. Argo plays a special role in GODAE because it is the only globally repeating subsurface ocean dataset, and is strongly complementary to its satellite counterparts. GODAE's vision is "A global system of observations, communications, modeling and assimilation, that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community" (http://www.bom.gov.au/bmrc/ocean/GODAE/).

CLIVAR: (Climate Variability and Predictability experiment of the World Climate Research Program). Argo provides a primary ocean dataset for this experiment targeting better understanding of the climate system, including its variability and predictability. (See http://www.clivar.org.) CLIVAR's aim is to exploit the research value of broadscale climate observations and focused process experiments. In this context, Argo measures the storage and transport of heat and freshwater globally on broad spatial scales.

Global CO2 Flux Map Project: Argo provides near surface salinity and temperature to the NOAA Office of Global Programs funded project directed at providing global maps of CO2 surface fluxes. The float data will be used in algorithms (developed from pCO2 observations) that provide estimates of surface carbon fluxes from surface salinity and temperature data.

US Argo Consortium Relevant Web Sites

Argo Science Team home page
http://www-argo.ucsd.edu

Argo Information Center
http://argo.jcommops.org

Scripps Institution of Oceanography
http://sio-argo.ucsd.edu

Woods Hole Oceanographic Institution
http://ursa.whoi.edu/~argo/

University of Washington
http://flux.ocean.washington.edu/argo/

NOAA PMEL
http://floats.pmel.noaa.gov/argo

NOAA PMEL(Delayed Mode QC))
http://www.aoml.noaa.gov/phod/ARGO/HomePage/

NOAA PMEL (General)
http://floats.pmel.noaa.gov/floats

US GDAC
http://www.usgodae.org

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Other Refereed Publications

Argo data are now appearing in referred publications with increasing frequency. The Argo bibliography (http://www.argo.ucsd.edu/FrBibliography.html) lists 40 papers published so far in 2005. This compares with 27 each in 2003 and 2004.

2. Gliders for Climate Observations

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PROJECT SUMMARY

The objectives of the Consortium on the Ocean's Role in Climate (CORC) include maintaining developmental elements of the ocean climate observing system.

New observational techniques being developed include underwater gliders that operate like autonomously profiling Argo floats, which cycle vertically in the ocean under changing buoyancy, except that the gliders have wings and a control system so that they glide forward as they both ascend and descend. While strictly small AUVs, the slow speed of gliders makes them more nearly relocatable profiling floats. It is believed that gliders can be valuable augmenting the Argo Array in regions like the equator, boundaries or other regions where it is important to be able to control observation positions.

FY 2005 PROGRESS

This year we completed development of a high-frequency Acoustic Doppler Profiler (ADP) for the Spray glider. Inherently, the wings on a glider make it possible to accurately measure their velocity through the water by measuring descent rate. Integrating this over a dive cycle and comparing the distance moved through the water with GPS positioning provides an accurate measurement of velocity averaged over the depth range of glider profiling. A 750-kHz Sontek ADP was added to the Spray glider to measure shear over about 25-30 m of depth. Integrating this shear and referencing it to an integration constant based on the measured depth-average flow provides a profile of horizontal velocity. Figure 1 shows the comparison of velocity measured in this way with velocity measured from a nearby shipboard Acoustic Doppler Current Profiler that measured down to the glider operating depth. In practice, several of these glider profiles would be averaged from successive dives to achieve a climatically significant velocity measurement.

In addition to the ADP, we have improved Spray reliability and performance. Significant changes introduced this year are (1) a new pumped Sea Bird CTD with significantly improved accuracy and reliability as compared with our earlier sensor; (2) improved hydraulic bladder manufacturing process to avoid the residual talc contamination from the previous procedure; (3) addition of a second particle filter to catch any contamination coming from the bladder; (4) a new electric motor for the hydraulic system replacing one that did not meet specifications and burned out under operation to 1000 m; (5) modification of various fittings in the hydraulic system to minimize the chance of air leaks; and (6) addition of an air trap to collect any small bubbles in the hydraulic oil which could cause vapor-lock of the hydraulic pump.

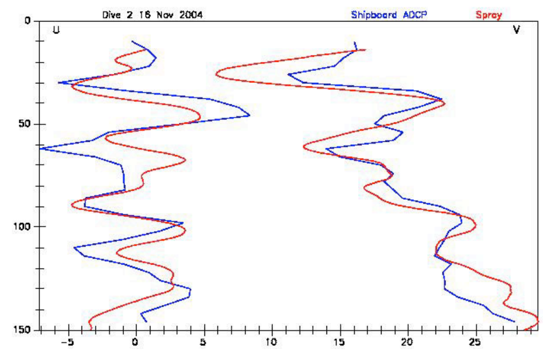

Figure 1. Profiles of east (left) and north (right) components of velocity measured by integrating shear from an ADP on a Spray glider (red) and from a 300 kHz shipboard ADCP operated near by. The ADCP was averaged over the approximately 30 minutes that it took Spray to profile over 150 meters. The V profiles are offset 20 cm/s.

Two surveys from this year show the capabilities of Spray in monitoring climatically important regions where randomly placed profiling Argo floats do not provide sufficiently controllable sampling. The first, shown in Figure 2, is a 700 km section southeast of San Diego. Physical climate variations are associated with significant changes in the California Current ecosystem and gliders provide an economical way to monitor these changes to test theories on what aspect of the physical variability impacts which aspect of the ecosystem.

This year's second example is a collaboration with William Kessler (PMEL) and the IRD laboratory in New Caledonia to sample the Pacific's South Equatorial Current (SEC). This current is the primary shallow source feeding the western equatorial Pacific and, consequently, a potential factor in modulating, or even triggering, the ENSO cycle. New Caledonia is ideally situated to monitor the SEC, sitting between a branch that passes to the south and then northward between New

Caledonia and Australia and another branch to the north, mainly to the south of the Solomon Islands, which flows directly to the equatorial western boundary. Our first target was the northern branch. IRD deployed a CORC glider near the Solomon Islands and it is at this time approaching Noumea, where it will be recovered. Figure 3 shows the track and depth-averaged current. This coupled with geostrophic shear allows measurement of volume and heat transport to 1000 m depth.

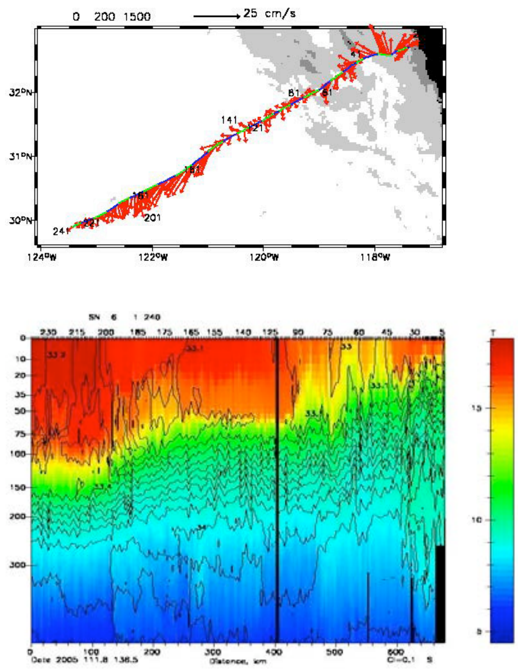

Figure 2. A Spray glider section through the California Current southeast of San Diego. The upper plot shows the outbound track and arrows represent the depth-averaged current from 0 to 500 m. Depth shading is 0, 200 and 1500 m. The lower plot shows the temperature and salinity distribution. The color contouring depicts temperature and contour lines represent salinity.

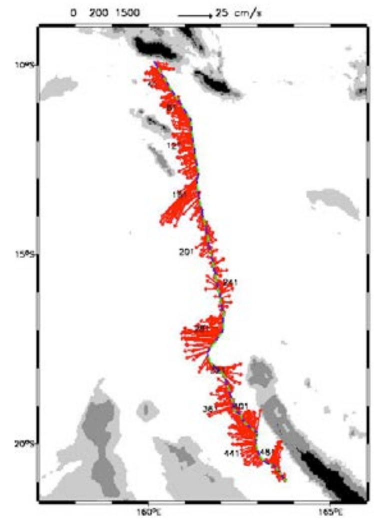

Figure 3. Spray section from Solomon Islands to New Caledonia. Arrows show depth average velocity in this section across the South Equatorial Current.

3. Improved Salinity Measurements

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PROJECT SUMMARY

Assessing the strength of the hydrologic cycle over the ocean is a challenging problem. One important indicator of the water cycle is the salinity structure of the upper ocean. To this end we are focusing on a basic climate observation need, which is to improve the quality of oceanic salinity instrumentation.

This project focuses on instrumentation used to measure salinity on autonomous vehicles. We have advanced automated salinity measurement technology by working with Falmouth Scientific, Inc. to improve their conductivity cell and by assisting in development of their "Excell" Float CTD. This work addresses problems with present instrumentation and provides diversified technology sources for Argo salinity measurements.

FY 2005 PROGRESS

We have long been concerned with the challenge of assessing the strength of the hydrologic cycle over the ocean. One important indicator of the water cycle is the salinity structure of the upper ocean. This project focuses on instrumentation used to measure salinity on autonomous vehicles. To this end, we have worked with Falmouth Scientific, Inc. (FSI) to improve conductivity cell performance and develop of the FSI "Excell" Float CTD. Early versions of the Excell were tested extensively for electronic performance and tuned to have proper dynamic response. Data from such floats was used to link low surface salinity to river plumes visible from the SeaWifs satellite (Hu et al., 2004). Later models are performing much better than initial versions. Several FSI-equipped SOLO floats were deployed in the eastern tropical Pacific last year as part of the CORC/ARGO array.

Effort has also gone into studies of the dynamic response of the sensors. Dynamic response is always a concern with salinity measurements from moving sensors, as temperature and conductivity cells inevitably have different response times, with different speed dependencies. This leads to an error in the calculated salinity which can be significant in strong thermoclines, and leads to subtle errors elsewhere. Salinity spiking and density inversions from SeaBird-CTD-equipped floats in ARGO have been a noticeable problem in some areas (G. Johnson, personal communication). Salinity spikes can be avoided if the dynamic response characteristics of temperature and conductivity cells are understood and accounted for prior to calculation of salinity. This is an especially important issue for profiling floats as transmission of raw data is impractical and data reduction must be done on-board.

In order to address the dynamic response problem we have constructed a special double-diffusive-interface tank capable of long-term maintenance of a very sharp temperature/salinity step (Schmitt et al, 2005). Traversing the CTD through the interface reveals the sensor mismatches and allows development of an appropriate filter to optimize the accuracy of the salinity calculations. This has been done for the Excell float CTD. Figure 1 shows the dynamic response tank we are using for these tests. A new speed control mechanism was installed for tests of the SeaBird pumped CTD.

Dynamic response testing of the Sea-Bird has been completed and a rather complex response function revealed. Figure 2 shows average scaled conductivity and temperature data from 11 such trials. Eleven plunge tests were averaged to account for the random timing between the slow Sea-Bird sample rate and the passage through the interface. Issues that can be identified in this type of plot are: 1) the relative placement of the temperature and conductivity probes, 2) the time constant of the temperature probe, and 3) the thermal mass

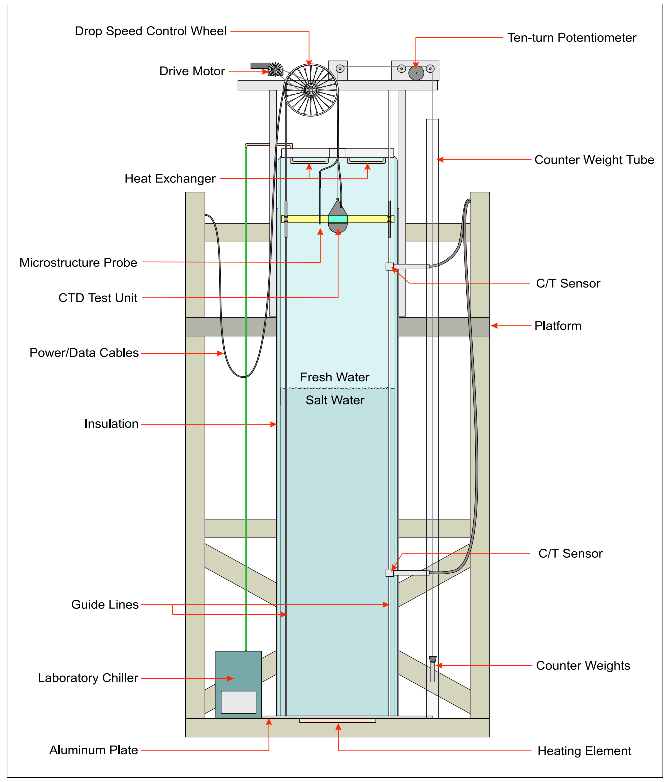

Figure 1. The double diffusive dynamic response tank used for tests of float CTDs. The 3 ft diameter pipe is 15 ft deep with an aluminum plate bottom. A heating element drives convection in the lower salty water and a heat exchanger cools the top of the upper fresh water. A computer controlled winch lowers the instruments through the sharp interface at a set speed. Sensors monitor the temperature and salinity of the mixed layers.

of the conductivity cell. In addition, there appear to be electronic drift issues that complicate the development of a suitable correction algorithm. A correction algorithm for the lag issues revealed in these tests was developed, but deemed not necessary as the major design features are largely compensating.

The greatest problem with the Seabird appears to be the thermal mass effect of the conductivity cell, which appears to have a longer time constant than can be readily sampled in this tank. We are planning to build a deeper tank and expect to be able to perform additional tests later in 2006.

To this end, we have worked with Falmouth Scientific, Inc. (FSI) to improve conductivity cell performance and to develop the FSI "Excell" Float CTD. Several FSI-equipped SOLO floats have now been deployed in the eastern tropical Pacific as part of the CORC/ARGO array.

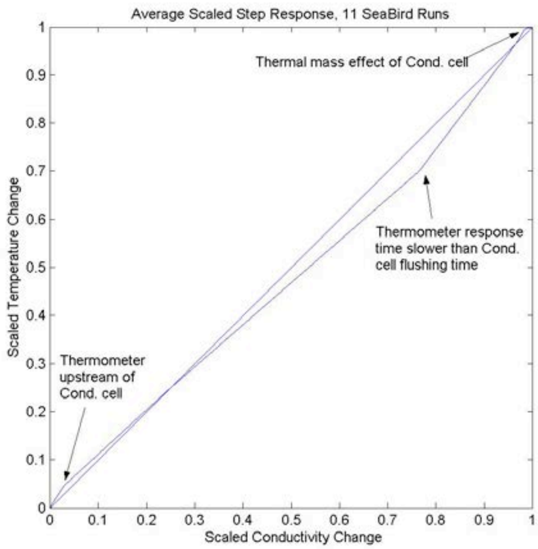

Figure 2. The average scaled step response from 11 plunges of the Sea-Bird float CTD through the double diffusive interface. The fall speed was 10 cm/sec and only data from the moving portion of the plunge were used. The instrument starts in the cold-fresh upper layer (0,0) and traverses to warm fresh (1,1). The deviation of the data from a straight line is indicative of lag and response time issues as shown.

The project also focuses on studies of the dynamic response of the sensors. This is always a concern with salinity measurements from moving sensors, since temperature and conductivity cells inevitably have different response times, with different speed dependencies. This mismatch leads to an error in the calculated salinity, which can be significant in strong thermoclines, and which leads to subtle errors elsewhere. Salinity spiking and density inversions from SeaBird-CTD-equipped floats in ARGO have been a noticeable problem in some areas (G. Johnson, personal communication). Salinity spikes can be avoided if the dynamic response characteristics of temperature and conductivity cells are understood and accounted for prior to calculation of salinity. This is an especially important issue for profiling floats as transmission of raw data is impractical and data reduction must be done on-board. Experiments are being performed to develop an appropriate filter to optimize the accuracy of the salinity calculations.

1. Global Repeat Hydrographic/CO_2/ Tracer Surveys In Support Of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes

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PROJECT SUMMARY

1.1 General Overview

The Repeat Hydrography CO_2/tracer Program is a systematic and global re-occupation of select hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon (CFC) tracers and related parameters. It builds upon earlier programs (e.g., World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Survey (JGOFS) during the 1990s) that have provided full depth data sets against which to measure future changes, and have shown where atmospheric constituents are getting into the oceans. The Repeat Hydrography CO_2/tracer Program (Figure 1; Table 1) will reveal much about internal pathways and changing patterns that will impact the carbon sinks on decadal time scales. It is designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or man-

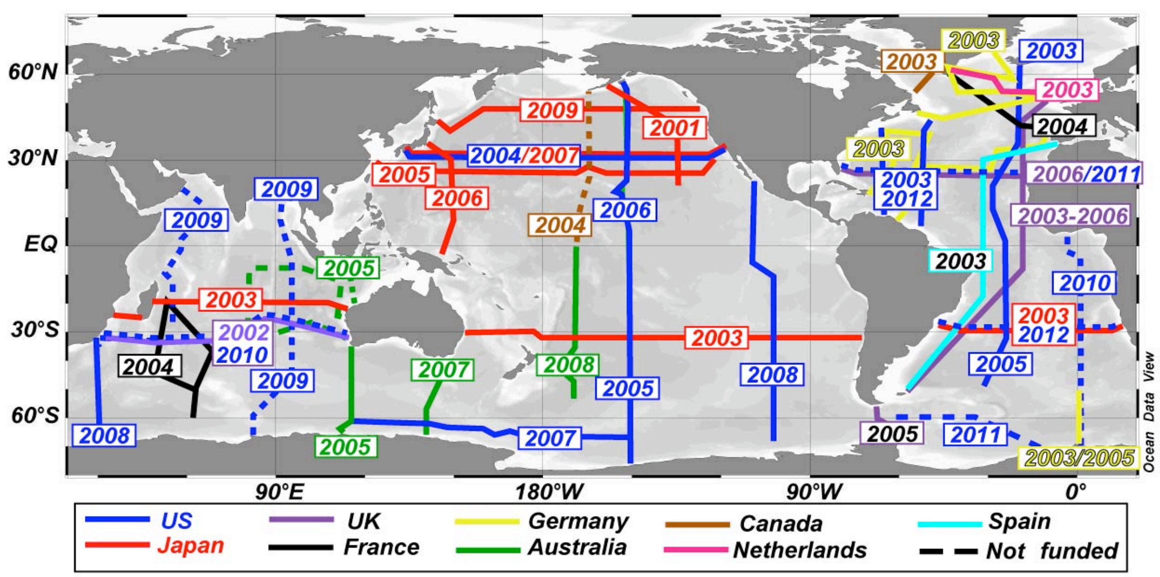


Figure 1. Global map of planned Repeat Hydrography CO_2/tracer Program hydrographic sections with carbon system measurements. Solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time. The U.S. A16S and P16S cruises in the South Atlantic and South Pacific, respectively, are designated with solid blue lines for calendar year 2005.

Table 1. Sequence of Repeat Hydrography CO_2/tracer cruises in the oceans for the decade starting in June of 2003.

Schedule of US CO2/CLIVAR Repeat Hydrography Lines (as of 10/05)

Dates	Cruise	Days	Ports	Year	Contact/Chief Scientist
					Overall Coordinator: Jim Swift, SIO
6/19/03-7/10/03	A16N, leg 1	22	Reykjavik-Madeira	1	Bullister, NOAA/PMEL
7/15/03-8/11/03	A16N, leg 2	28	Madeira - Natal, Brazil	1	Bullister, NOAA/PMEL
9/15/03-10/13/03	A20	29	WHOI - Port Of Spain	1	Toole, WHOI
10/16/03-11/07/03	A22	21	Port Of Spain - WHOI	1	Joyce, WHOI
6/13/04-7/23/04	P2, leg 1	41	Yokohama-Honolulu	2	Robbins, SIO
7/26/04-8/26/04	P2, leg 2	32	Honolulu - San Diego	2	Swift, SIO
1/11/05-2/24-05	A16S	45	Punta Arenas-Fortaleza	3	Wanninkhof/Doney; NOAA/AOML/WHOI
1/8/05-2/18/05	P16S	40	Tahiti-Wellington	3	Sloyan/Swift, WHOI/SIO
2006	P16N	57	Tahiti-Alaska	4	Feely/Sabine, NOAA/PMEL
austral summer 07	S4P/P16S	25.5	Wellington-Perth	5	
austral summer 07		25.5	Wellington-Perth	5	
2008	P18	32	Punta Arenas-Easter Island	6	
2008		35	Easter Island- San Diego	6	
2008	I6S	42	Cape Town	6	
2009	I7N	47	Port Louis/Muscat	7	future planning
2009	I8S	38	Perth- Perth	7	future planning
2009	I9N	34	Perth- Calcutta	7	future planning
2010	I5	43	Perth - Durban	8	future planning
2010	A13.5	62	Abidjan-Cape Town	8	future planning
2011	A5	30	Tenerife-Miami	9	future planning
2011	A21/S04A	42	Punta Arenas-Cape Town	9	future planning
2012	A10	29	Rio de Janeiro-Cape Town	10	future planning
2012	A20/A22	29	Woods Hole-Port of Spain-Woods Hole	10	future planning

Years 1-6 are funded.

induced activity. Global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can be followed through long-term measurements. Below the 2000m depth of the Argo array, Repeat Hydrography is the only global measurements program capable of observing these long-term trends in the ocean. The program will also provide data for the Argo sensor calibration (e.g., www.argo.ucsd.edu), and support for continuing model development that will lead to improved forecasting skill for oceans and global climate.

By integrating the scientific needs of the carbon and hydrography/tracer communities, major synergies and cost savings have been achieved. The philosophy is that in addition to efficiency, a coordinated approach will produce scientific advances that exceed those of having individual carbon and hydrographic/tracer programs. These advances will contribute to the following overlapping scientific objectives: 1) data for model calibration and validation; 2) carbon inventory and transport estimates; 3) heat and freshwater storage and flux studies; 4) deep and shallow water mass and ventilation studies; and 5) calibration of autonomous sensors.

1.2 National Linkages

The Repeat Hydrography CO_2/tracer Program is being implemented to maintain decadal time-scale sampling of ocean transports and inventories of climatically significant parameters in support of Objective 8 (Ocean Carbon Monitoring Network) of the Program Plan for Building a Sustained Observing Network for Climate. The sequence and timing for the sections (Fig. 1) takes into consideration the program objectives, providing global coverage, and anticipated resources. Also considered is the timing of national and international programs, including the focus of CLIVAR on the Atlantic in the early years of the program; the Ocean Carbon and Climate Change Program (OCCC) that emphasizes constraining the carbon uptake in the Northern Hemisphere oceans, in part, in support of the North American Carbon Program (NACP); and the international Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program. In addition, the proposed sections are selected so that there is roughly a decade between them and the WOCE/JGOFS occupation.

The scientific objectives are important both for the CLIVAR and the OCCC programs, and for operational activities such as Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). In mid-2001 the US scientific steering committees of CLIVAR (www.clivar.org) and the Carbon Cycle Science Program, (CCSP; www.carboncyclescience.gov) programs proposed the creation of a joint working group to make recommendations on a national program of observations to be integrated with international plans. Several community outreach programs and efforts have been implemented to provide information about the program, such as a web site with interactive forum (http://ushydro.ucsd.edu/index.html), articles in EOS (Sabine and Hood, 2002, Feely et al. 2005) and the JGOFS newsletter, as well as AGU and Ocean Science meeting forums. The Repeat HydrographyCO_2/tracer Program addresses the need, as discussed by the First International Conference on Global Observations for Climate (St. Raphael, France; October 1999), that one component of a global observing system for the physical climate/CO_2 system should include periodic observations of hydrographic variables, CO_2 system parameters and other tracers throughout the water column (Smith and Koblinsky, 2000; Fine et al., 2001). The large-scale observation component of the OCCC has also defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background (Doney et al., 2004; Figure. 1).

The CCSP has identified the critical need for the federal government to begin delivering regular reports documenting the present state of the climate system components. Through this program plan NOAA will develop the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system and to deliver regular reports on the ocean's contribution to the state of the climate and on the state of the observing system. The goal of this plan is to build and sustain the ocean component of a global climate observing system that will respond to the long-term observational requirements of the operational forecast centers, international research programs, and major scientific assessments.

1.3 Addressing NOAA's Program Plan)

The ocean is the memory of the climate system and is second only to the sun in effecting variability in the seasons and long-term climate change. It is estimated that the ocean stores 1000 times more heat than the atmosphere, and 50 times more carbon. Additionally, the key to possible abrupt climate change may lie in deep ocean circulation. Accordingly, the main objective of the repeat hydrography component of the sustained ocean observing system for climate is to document long-term trends in carbon storage and transport in the global oceans. This program will provide a composite global ocean observing system large-scale observations that includes: 1) detailed basin-wide observations of CO_2, hydrography, and tracer measurements; and 2) data delivery and management. This end-to-end ocean system will provide the critical "up-front" information needed for climate research and assessments, as well as long-term, climate quality, global data sets. At the same time, the data management system will provide the necessary data to serve the needs of the other federal agencies in accomplishing their missions.

1.4 International Linkages

Recognizing the need to develop an international framework for carbon research, various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the Intergovernmental Oceanographic Commission (IOC), and the Scientific Committee on Oceanic Research (SCOR) have worked together to develop research strategies for global carbon cycle studies. Based on the recommendations coming from these programs, NOAA and NSF have co-sponsored the Repeat Hydrography CO_2/tracers Program, with program direction coming from the Repeat Hydrography Oversight Committee (Richard Feely and Lynne Talley, co-chairs; http://ushydro.ucsd.edu/index.html). Many other nations are also sponsoring similar carbon studies that are comparable in focus and have been designed to be complimentary to our program(http://www.clivar.org/carbon_hydro/index.htm). Consequently, there is an immediate need for global-scale coordination of these carbon observations and research efforts to achieve the goal of a global synthesis. There is also an urgent need to critically assess the overall network of planned observations to ensure that the results, when combined, will meet the requirements of the research community. Because of these issues, the IOC-SCOR Ocean CO_2 Panel (http://www.ioc.unesco.org/iocweb/co2panel/) and the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) have initiated the International Ocean Carbon Coordination Project (IOCCP; http://www.ioc.unesco.org/ioccp/) to: (1) gather information about on-going and planned ocean carbon research and observation activities, (2) identify gaps and duplications in ocean carbon observations, (3) produce recommendations that optimize resources for international ocean carbon research and the potential scientific benefits of a coordinated observation strategy, and (4) promote the integration of ocean carbon research with appropriate atmospheric and terrestrial carbon activities. It is through the workings of the IOCCP and international CLIVAR that international coordination of data management, data synthesis and scientific interpretation of the global repeat sections results will be implemented. In addition, the Repeat Hydrography CO_2/tracer Program is being managed in accordance with the COSP Ten Climate Monitoring Principals.

FY 2005 PROGRESS

2.1 P16S Cruise Results

A hydrographic/carbon/tracer survey in the South Pacific Ocean was carried out from *R/V Roger Revelle*. The cruise departed from Papeete, Tahiti on 9 January, 2005. A meridional transect from 16° to 71° South along 150° West was completed (Figure 2). 111 full-depth CTD/rosette/LADCP casts (at one-half degree spacing), 4 shallow CDOM rosette casts, and 58 trace metals CTD/rosette casts were completed. Salinity, dissolved oxygen, and nutrients were analyzed for up to 36 water samples from each cast of the principal CTD/rosette program. Other parameters sampled included CFCs, helium, dissolved inorganic carbon, alkalinity, radiocarbon, tritium, several parameters related to dissolved organic matter, and nitrogen-15. Additional deployments included 12 ARGOS floats and 21 Bio-Optics casts. The cruise ended in Wellington, New Zealand on 19 February 2005.

TOTAL DISSOLVED INORGANIC CARBON (DIC)

The DIC analytical equipment was set up in a seagoing container modified for use as a shipboard laboratory. The analysis was done by coulometry with two analytical systems (PMEL-1 and PMEL-2) operated simultaneously on the cruise by Dr. Christopher Sabine (PMEL) and Miss Justine Afghan (SIO). Each system consisted of a coulometer (UIC, Inc.) coupled with a SOMMA (Single Operator Multiparameter Metabolic Analyzer) inlet system developed by Ken Johnson (Johnson et al., 1985,1987,1993; Johnson, 1992) of Brookhaven National Laboratory (BNL). In the coulometric analysis of DIC, all carbonate species are converted to CO_2 (gas) by addition of excess hydrogen to the seawater sample, and the evolved CO_2 gas is carried into the titration cell of the coulometer, where it reacts quantitatively with a proprietary reagent based on ethanolamine to generate hydrogen ions. These are subsequently titrated with coulometrically generated OH-. CO_2 is thus measured by integrating the total change required to achieve this.

The coulometers were each calibrated by injecting aliquots of pure CO_2 (99.995%) by means of an 8-port valve outfitted with two sample loops (Wilke et al., 1993). The instruments were calibrated at the beginning of each station with a set of the gas loop injections.

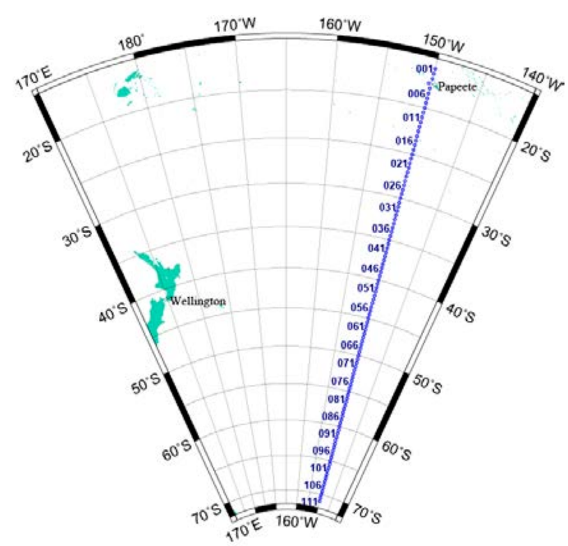


Figure 2. Cruise Track of Repeat Hydrography P16S along 150°W during Jan - Feb 2005 in the South Pacific.

Subsequent calibrations were run either in the middle or end of the cast if replicate samples collected from the same Niskin, which were analyzed at different stages of analysis, were different by more than 2 μmol kg^{-1}.

Secondary standards were run throughout the cruise on each analytical system; these standards are Certified Reference Materials (CRMs) consisting of poisoned, filtered, and UV irradiated seawater supplied by Dr. A. Dickson of Scripps Institution of Oceanography (SIO), and their accuracy is determined shoreside manometrically. On this cruise, the overall accuracy and precision for the CRMs on both instruments was -1.7±0.8 μmol kg^{-1} (n=63) and -2.4±0.7 μmol kg^{-1} (n=64) for PMEL-1 and PMEL-2, respectively. Preliminary DIC data reported to the database have not yet been corrected to the Batch 67 CRM value, but a more careful quality assurance to be completed shoreside will have final data corrected to the secondary standard on a per instrument basis.

Samples were drawn from the Niskin-type bottles into cleaned, precombusted 300-mL Pyrex bottles using silicone tubing. Bottles were rinsed three times and filled from the bottom, overflowing half a volume, and care was taken not to entrain any bubbles. The tube was pinched off and withdrawn, creating a 3-mL headspace, and 0.2 mL of 50% saturated $HgCl_2$ solution was added as a preservative. The sample bottles were sealed with glass stoppers lightly covered with Apiezon-L grease, and were stored at room temperature for a maximum of 24 hours prior to analysis.

DIC values were reported for 2882 samples or approximately 75% of the tripped bottles on this cruise. Full profiles were completed at odd numbered stations on whole degrees, with replicate samples taken from the surface, oxygen minimum, and bottom depths. On the even numbered (half degree) stations, as many samples as possible were drawn based on the current sample throughput; replicates were collected from the surface and bottom bottles. Typical even numbered stations had between 8 and 20 bottles sampled.

Duplicate samples were drawn from 256 bottles and interspersed throughout the station analysis for quality assurance of the coulometer cell solution integrity. The average of the absolute value of the difference between duplicates was 1 μmol kg^{-1} for both systems. No systematic differences between the replicates were observed.

The only significant problem encountered on this cruise was a failure of the gas loop calibration system on PMEL-2 during the last week of running stations. The problem was noted when calibrations started giving unusually low calibration values that also produced unusually low CRM results. The problem was isolated to the gas sample valve but could not be repaired without significant loss of sample analysis time. Instead, we manually entered a calibration factor based on the mean value obtained from the previous month's worth of calibrations. The manually entered calibration factor was confirmed by analyzing CRMs with every station, comparing replicate samples between PMEL-1 and PMEL-2, and careful inspection of deep water values analyzed on the two systems. We do not believe this problem has compromised the data in any way.

Underway pCO2

The underway surface pCO_2 system was started shortly after leaving Papeete, Tahiti. The semi-autonomous system analyzes surface water collected from the ship's uncontaminated seawater supply and marine air from the ship's bow on a repeating hourly cycle. The first quarter of each hour is devoted to calibration with four CO_2 standards (Feely et al., 1998). A second order polynomial calibration curve is calculated for the LiCor 6262 infrared detector. The remaining time in each hour is used to measure equilibrator air (15 min), bow air (15 min), and equilibrator air once again (15 min). The analytical precision of the system is estimated to be approximately 0.3-0.4 ppm for seawater and for air.

The underway system operated without problems until January 27, 2005 when rough weather forced the uncontaminated seawater supply to be shut down. On January 28th, the system was re-plumbed to take seawater from the sea-chest which could still operate in rough weather. On February 3rd, the weather had calmed again so the seawater intake was switched back to the uncontaminated supply from the bow. The system continued to run until February 8th when the computer running the underway system failed preventing any additional analyses for the remainder of the cruise.

Preliminary Results

The DIC data from this cruise are still undergoing post cruise processing and quality assessment procedures, but appear to be of very high quality. This cruise sampled the South Pacific Ocean from Subtropical zone to the Antarctic zone crossing the Sub-antarctic Front at ~53°S, the Polar Front at ~57°S, and the Antarctic Circumpolar Front at ~58°S. A section of the DIC data shows strong vertical and horizontal gradients in the concentrations consistent with anticipated circulation features (Figure 3). The black dots in figure 3 indicate the location of the carbon measurements. The previous occupation of this line was during the WOCE global survey in 1993. Figure 4 shows the change in DIC between these cruises (approximately 12 years). Preliminary results indicate much higher DIC values at the southern end of the section.

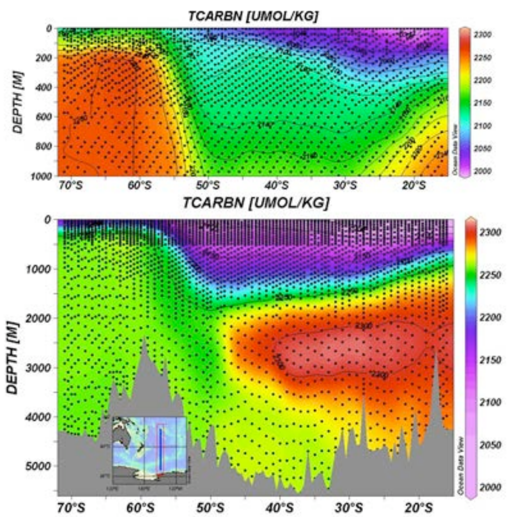


Figure 3. DIC along the P16S section in the South Pacific along 150°W.

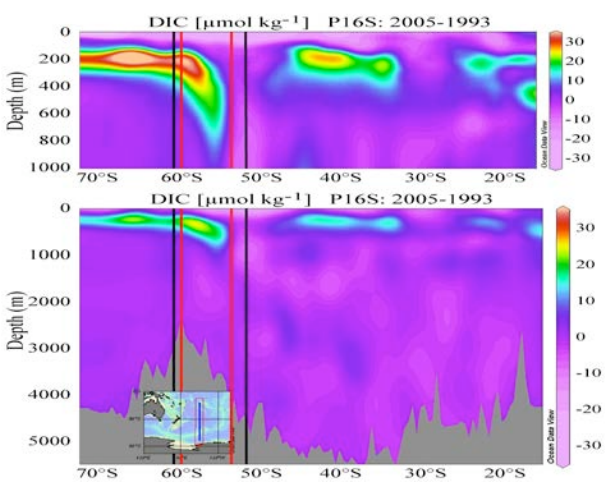


Figure 4. DIC difference (2005-1993). The white vertical lines show the position of the Polar and Sub-antarctic Fronts, respectively, in 2005 and the red vertical lines show the positions of these fronts in 1993. The increases in DIC are the result of a combination of processes including: anthropogenic CO_2 invasion, and changes in circulation and biogeochemistry.

2.2 A16S Cruise in the South Atlantic

On January 11 2005 the NOAA Ship *Ronald Brown* left Punta Arenas, Chile to reoccupy WOCE Section A16S and a portion of WOCE Section A23 (Figure 5). The ship arrived in Fortaleza, Brazil 45 days later on 24 February 2005 after a very successful cruise. In all 121 full water column stations were occupied along sections from 60°S to 2° 20'S at 30' latitude or closer spacing. Stations were occupied slightly farther north than planned, allowing a generous 9-station overlap with the 2003 reoccupation of A16N for detailed measurement inter-comparisons. Rik Wanninkhof (AOML) and Scott Doney (WHOI) were co-chief scientists on the cruise. Of the 31 participants on the cruise, 14 were covered by funds from this effort (5 from AOML, 3 from PMEL, 2 from CIMAS, 2 from JISAO, 1 from UW, and 1 from RSMAS).

NOAA took the lead on measuring core hydrographic parameters (CTD/O_2, salinity, dissolved oxygen, CO_2 and nutrients) for that cruise. Participating scientists from PMEL, AOML and 13 other scientific institutions made a wide variety of atmospheric and oceanic measurements. Atmospheric (CO_2, chlorofluorocarbons, aerosols) and near surface seawater (temperature, salinity, pCO_2, fluorescence, ADCP) measurements were made while underway along the cruise track. Two new instruments to measure surface water carbon properties were successfully tested. Twelve ALACE profiling floats were deployed along the section. Full water

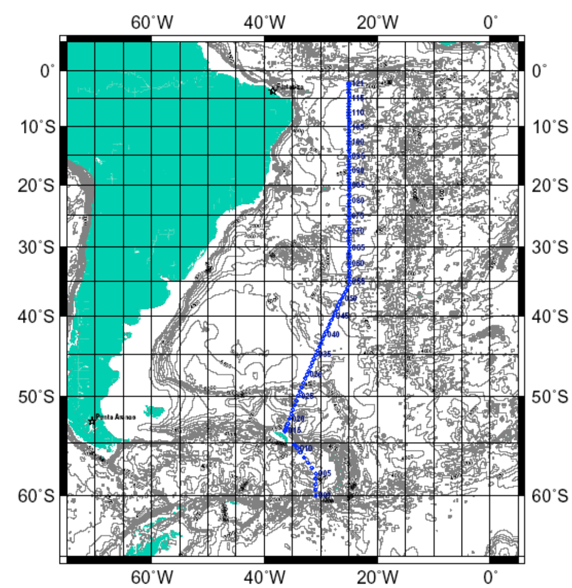


Figure 5. Cruise track and station number of CLIVAR CO_2 repeat hydrography cruise A16 S superimposed on a map of the South Atlantic including bottom bathymetry

column CTD/rosette casts were made at 121 stations, with ≈4300 discrete seawater samples collected using a specially designed 36-position 12-liter rosette package. In addition to the CTD, the rosette frame held a lowered ADCP, transmissometer and particulate inorganic carbon sensors (2X).

Seawater samples were analyzed on board ship for salinity, dissolved oxygen, nutrients, Total CO_2 (DIC), Total Alkalinity (TA), pCO_2, pH, chlorofluorocarbons (CFCs), and hydrochlorofluorcarbons (HCFCs). Water samples were collected for shore-based analyses of helium, tritium, dissolved organic carbon, particulate organic and inorganic carbon, ^{13}C and ^{14}C. As the samples were analyzed on board, the data were collected and compiled by the data manager, allowing near real-time examination and comparison of the data sets as they were generated. A ship based web server that included historical data and graphical tools facilitated this work. The server can now be found at: http://sts.ucsd.edu/cruise/a16s/hydro/. The Scripps operations group performed data management with funding from the National Science Foundation. A screen shot of the ship-based web page is shown in Figure 6.

The A16S CTD and bottle set is publicly accessible on line at: http://whpo.ucsd.edu/data/tables/onetime/1tim_atl.htm#A16. The cruise is designated as A16S_2005 with Expocodes: *33RO200501*. Final calibration and processing of the cruise data set is nearly finished and we anticipate completing this process by the end of FY-2005.

Hydrography

The hydrography effort (CTD/O_2 and associated equipment) was led by PMEL with assistance with personnel and equipment from AOML. The PMEL hydrography group work in preparation for this cruise included readying and assembling the rosette frames, Niskin bottles, CTD/O_2s, altimeters, load cells, 12 kHz pingers, LADCPs, cabling, terminations, and other underwater equipment. This effort included building a new bracket to accommodate the upward-looking 300 kHz LADCP on the primary frame. PMEL also acquired the necessary standard seawater, cruise supplies, and shipped the bulk of the CTD/O_2 and LADCP gear to Punta Arenas.

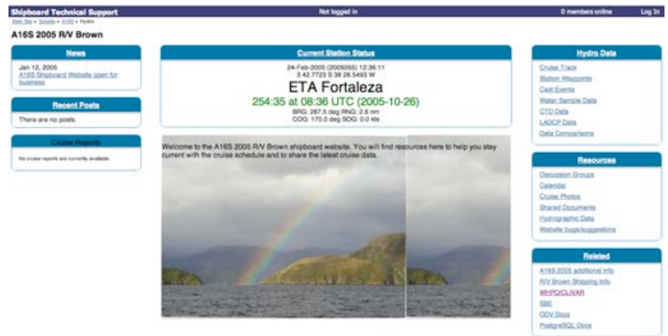


Figure 6. Screen shot of the front page of the shipboard data web server showing the utilities.

AOML provided a back-up CTD and fully equipped 24-bottle frame. While at sea, the hydro group acquired CTD/O_2 data, ran salinity samples, monitored sensor performance, and performed preliminary calibrations of the CTD/O_2 temperature, salinity, and oxygen sensors.

Since the cruise the CTD/O_2 sensors have undergone post-cruise calibrations. Final calibrations of CTD/O_2 temperature, salinity, pressure, and oxygen data have been completed. The data are believed to be accurate to within 0.002°C, 0.002 PSS-78, 3 dbar, and 1.0 μmol kg^{-1} or better, respectively. The bottle salinity data quality flags have been revised and the final CTD/O_2 and salinity data and quality flags have been submitted to the CLIVAR and Carbon Hydrographic Data Office (CCHDO). The CTD/O_2 data calibration, processing procedures and quality control checked are detailed in a comprehensive cruise report (Wanninkhof and Doney, 2005). The AOML hydrography group provided a 24-position backup CTD frame, carousel, CTD and 2 complete sensor sets. AOML also readied the autosal interface and altimeter. While at sea, CTD/O_2 data was acquired, salinity samples analyzed, sensor performance monitored, and preliminary calibrations of the CTD/O_2 (temperature, salinity, and oxygen sensors) were preformed. . Much of the data reduction for discrete oxygen samples taken on the A16S cruise has been completed and the preliminary data has been submitted to the CLIVAR and Carbon Hydrographic Data Office (formerly WOCE Hydrographic Program Office).

Nutrients

Dissolved nutrients (phosphate, silicic acid, nitrate and nitrite) were drawn from all bottles on all casts in 40 ml HDPE Boston Round sample bottles that had been stored in 10% HCl and rinsed four to five times with sample before filling. A replicate was always drawn from the deep bottle for analysis on the subsequent station. All samples were brought to room temperature prior to analysis. Nutrient samples were measured using automated continuous flow analysis with a segmented flow and colorimetric detection. The four-channel auto analyzer was customized using components from various systems. Glass coils and tubing from the Technicon Autoanalyzer II were used for analysis of phosphate, and micro-coils from Alpkem were used for the other three analyses. Few replicate analyses were conducted for samples in the upper water, and the precision of nitrate was determined from those samples with concentrations >0.05 mM. The precision of phosphate, silicic acid and nitrate was within 2% of full scale. A summary can be found in Table 2.

Table 2. Summary of number of nutrient samples taken and estimated precision.

	Phos-phate	**Silicic Acid**	**Nitrate**	**Nitrite**
Number of samples	4286	4286	4243	4286
Number of replicates	755	759	680	19*
Average standard deviation (µM)	0.01	0.4	0.08	0.005
Percent deviation	0.8%	1.7%	1.4%	2%

* Samples with nitrate concentrations higher that 0.05 mM.

Oxygen

Oxygen samples were drawn from all 12-l Bullister bottles. A significant investment in effort to improve the oxygen analyses that had experienced some problems during the 2003 A16S cruise. These improvements included attracting a PI, C. Langdon of RSMAS, to lead the O_2 efforts, improving shore side preparation, and better-defined analysis protocols and data checks on the ship.

Oxygen samples were drawn into calibrated 140 ml iodine titration flasks. One-ml of $MnCl_2$ and one-ml of NaOH/NaI were added, the flask stoppered, and shaken. Deionized water was added to the neck of each flask to create a water seal. The flasks were stored in the lab in plastic totes at room temperature for 1-2 hours before analysis.

Thirty-six samples were drawn from most stations (exceptions for shallow stations where fewer bottles tripped or for bottles with visible problems during sampling, e.g., leaking, open vent cap, etc.) for a total of 121 stations.

Total number of samples: 4659

Total number of samples flagged after initial shipboard reduction of quality control:
Questionable (QC=3): 37
Bad (QC=4): 4
Not reported (QC=5): 3

Two to three sets of duplicates were drawn at each station for a total of 265 duplicates. The average standard deviation of the duplicates was 0.25 µmol kg^{-1}. A composite cross section for difference in apparent oxygen utilization values (AOU=O_2- O_2 at saturation) changes between the late 80-ties and the 2003/2005 repeat hydrography cruises is shown in Figure 7. Large increases in AOU are observed in the upper thermocline that are speculated to be caused by changes in ventilation. A full attribution of the causes of the large changes has still to be performed.

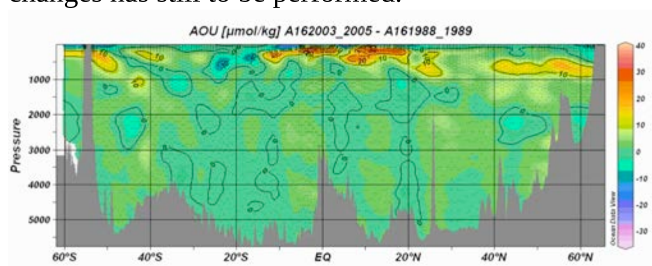


Figure 7. Cross section of AOU difference between the 2003/2005 CLIVAR CO_2 repeat hydrography cruises and the Oceanus-202 and SAVE/HYDROS cruise in 1988/89.

Inorganic Carbon measurements

DIC samples

DIC samples were collected at every degree from 36 depths with three replicate samples. Some samples were also collected at every half-degree. The replicate seawater samples were taken from the surface, 1000 m, and bottom Bullister bottles and run at different times during the analysis sequence. No systematic difference between the replicates was observed. There was no systematic dependency of results with an amount of carbon titrated for a particular cell either.

Total number of samples analyzed: 2482

Total number of samples flagged after initial shipboard data reduction of quality control:
Good (QC=2): 2245
Duplicates (QC=6): 180
Questionable (QC=3): 31
Bad (QC=4): 20
Not Reported (QC=5): 6

The instrument has a salinity sensor, but all DIC values were recalculated to a molar weight (µmol kg^{-1}) using density obtained from the CTD's salinity sensor. The DIC values were corrected for dilution by 0.2 ml of $HgCl_2$ used for sample preservation. The correction factor used for dilution was 1.00037. A correction was also applied for the offset from the CRM. This correction was applied for each cell using the CRM value obtained in the beginning of the cell. The results have undergone initial quality control on the ship using property plots: DIC-Depth, DIC-Potential Temperature, DIC-AOU, DIC-NO_3; DIC-SiO_3, DIC-PO_4, DIC-TAlk, and DIC-pH. Also DIC-LAT-Depth contour plots were used to analyze the quality of the data. Final quality control of the inorganic carbon parameters will occur by the end of 2005.

A composite cross section for difference in DIC changes between the late 80-ties/early 90-ties and the 2003/2005 repeat hydrography cruises is shown in Figure 8. Increases in DIC are observed in the upper water column that are caused by a combination of invasion of anthropogenic CO_2 and changes in ventilation and remineralization. Separation of the different contributions has still to be performed.

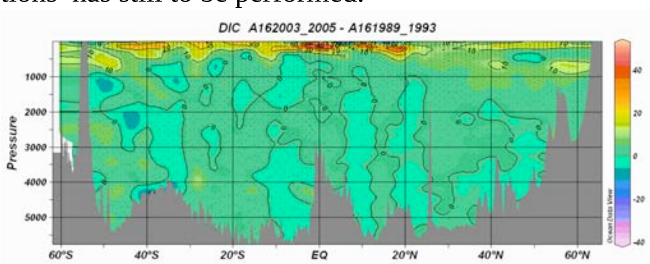


Figure 8. Cross section of DIC difference between the 2003/2005 CLIVAR CO_2 repeat hydrography cruises and the NOAA/OACES N_Atl-93 cruise in 1993 and SAVE/HYDROS cruise in 1988/89.

Discrete pCO_2 measurements

Measurements of discrete pCO_2 at a constant temperature of 20°C is a unique skill of personnel at the NOAA laboratories. The measurement offers the ability to overdetermine the inorganic carbon system thereby making it possible to independently verify the integrity of carbon system parameters (see below). On the A16N and A16S cruises pH was measured as well by the group of Prof. Millero at RSMAS thereby making it possible to assess biases in carbonate dissociation constants. This "redundancy" of measurements to cross check quality of data is of critical importance to insure the integrity for climate quality data. pCO_2(discrete) is also very sensitive to changes in inorganic carbon and alkalinity in the ocean making it a good indicator to change. The measurement is challenging requiring an equilibration between water and an isolated headspace. In particular issues with water vapor interference and corrections to perturbation have affected the accuracy that is determined through comparison with CO_2 in air gas standards.

For A16S there was no dedicated pCO_2 analyst onboard so only a subset of samples could be analyzed. Thirty samples were drawn every fourth station (@ 2 degree intervals) for a total of 29 stations.

Total number of samples: 847

Total number of samples flagged after initial shipboard data reduction of quality control:

Questionable (QC=3): 9

Bad (QC=4): 1

Not reported (QC=5) (tests): 5

Duplicates (QC=6): 9

Uncertainty based on duplicate sampling of the same Bullister bottle for pCO_2 analysis was determined on select stations of the cruise. The comparisons are presented in Table 3.

Table 3. Duplicate discrete pCO_2 samples.

Station	Sample No.	pCO_{2av}	ΔpCO_2	% difference
5	203	1093.8	3.0	0.3
5	209	1089	2.3	0.2
9	103	1087.3	1.5	0.1
9	105	1088.8	2.4	0.2
9	109	1081.6	2.7	0.2
21	135	572.7	0.4	0.07
49	121	838.	0.4	0.05
65	121	756.1	5.6	0.7
93	124	1040.3	2.3	0.2

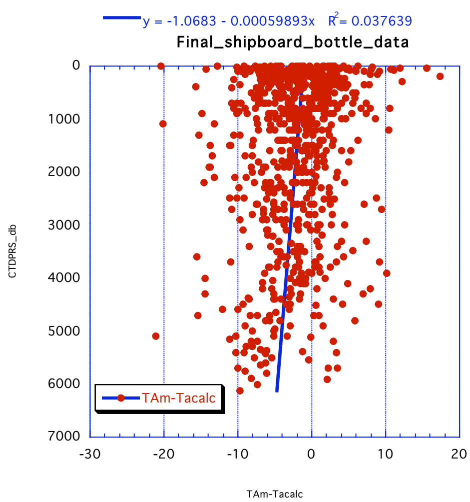
pCO_{2av} = average of the duplicate samples.

ΔpCO_2 = absolute difference between the duplicates

% difference = $\Delta pCO_2/pCO_{2av} * 100$

Internal consistency of carbon parameters

The comparison of measured inorganic carbon parameters with calculated values using the carbonate dissociation constants and two other of the four measured parameters (DIC, pCO_2, TA, and pH) is a powerful way to assess consistency and accuracy of all the measurements. On the A16S cruise the parameters were consistent to within the known uncertainty of analysis. Comparison of TA with TA calculated from pCO_2 and DIC is shown in Figure 9. The preliminary shipboard data showed an average Difference of -2.03 µmol kg^{-1} ± 4.91, µmol kg^{-1} N= 768. The agreement and precision is significantly better than previous cruises.



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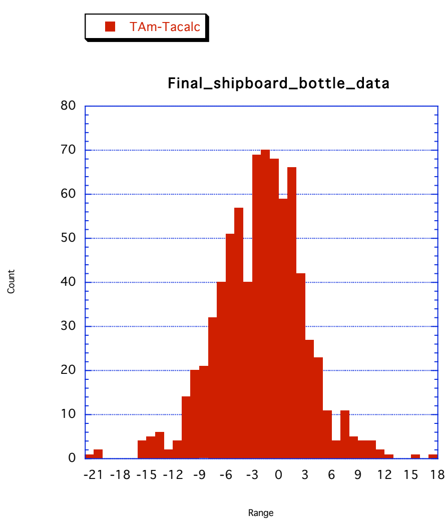

B

Figure 9. Comparison of TA with TA calculated from pCO_2 and DIC versus depth (A). The distribution of differences are shown as a histogram (B).

As outlined above the inorganic carbon data undergoes a rigorous multi-step quality control with the steps outlined in Table 4. As shown in the table, the data reduction is on schedule for final submission by the end of 2005.

Table 4. Status of data reduction and reporting for DIC, TAlk, pH, and discrete pCO_2

	A16N (2003)	A16S (2005)
Compile Dataset	completed	completed
Additional QC	completed	underway
Crossover Analysis	completed	completed prelim. data
Final Data Calibration	completed	December 2005
Carbon Thermodynam	completed	completed prelim. data

Chlorofluorocarbons

In FY2005, the PMEL Chlorofluorocarbon (CFC) Tracer group participated on the 45 day long A16S cruise. The CFC analysis were performed jointly with Dr. Mark Warner at the University of Washington. Three CFC analysts participated on the A16S cruise: J. Bullister, M. Warner and E. Wisegarver.

Samples for the analyses of dissolved CFC-11, CFC-12, CFC-113, were drawn from ~2400 of the ~4200 water samples collected during the expedition. Because of the importance of the relationship between the uptake of CFCs and anthropogenic carbon in the ocean, care was taken to coordinate the sampling of CFCs with the sampling for DIC, alkalinity. pH and pCO_2. In almost all cases a CFC sample was collected and analysed from the bottles sampled for carbon parameters.

Concentrations of CFC-11 and CFC-12, CFC-113 in air samples, seawater, and gas standards were measured by shipboard electron capture gas chromatography (EC-GC) using techniques modified from those described by Bullister and Weiss (1988). A new technique was developed before the cruise with the goal of allowing carbon tetrachloride (CCl_4) to be analysed on the same samples as the CFCs. This method was tested on the A16S cruise, and with further development, may become a standard procedure on future cruises, allowing this potentially useful tracer to become a more routine measurement.

The analytical systems were calibrated frequently, using a standard gas (PMEL cylinder 45191) of known CFC composition. CFC and CCl_4 concentrations in air and seawater samples were determined by fitting their chromatographic peak areas to multi-point calibration curves, generated by injecting multiple sample loops of gas from the standard into the analytical instrument.

Concentrations of the CFCs and CCl_4 in air, seawater samples, and gas standards were reported relative to the SIO98 calibration scale (Prinn et. al., 2000). Dissolved CFC and CCl_4 concentrations are given in units of picomoles per kilogram seawater (pmol kg^{-1}). On this expedition, based on the analysis of 103 duplicate samples, we estimate precisions (1 standard deviation) of 0.48% or 0.004 pmol kg^{-1} (whichever is greater) for dissolved CFC-11, 0.67% or 0.003 pmol kg^{-1} for CFC-12 measurements, 2.6% or 0.004 pmol kg^{-1} for CFC-113, and 1.9% or 0.005 pmol kg^{-1} for CCl_4 measurements. The overall quality of the core CFC measurements (CFC-11 and CFC-12) was very good and fully meet WOCE/CLIVAR quality standards.

The quality checked data have been submitted to the CCHDO office and are available at: http://whpo.ucsd.edu/data/co2clivar/atlantic/a16/a16s_2005a/index.htm

Initial analysis of the results from the A16S repeat CFC sections has begun. Figure 10 shows the observed CFC-12 concentrations from the 2005 A16S in the South Atlantic combined with those from the 2003 A16N cruise in 2003 in the North Atlantic. Figure 11 shows the changes in dissolved CFC-12 concentrations along this section between the 2003-2005 occupation and the 1988-1993 occupation.

The CFC-12 concentration section highlights water which has had substantial ventilation during the period since CFCs have been present in the atmosphere. Of particular interest is the strong penetration of CFCs in the upper water along the entire section, the strong subsurface signal of CFCs in Antarctic Intermediate Waters (AAIW) and Antarctic Bottom Waters (AABW) south of ~ 30°S, and in Labrador Sea (LSW) and North Atlantic Deep Waters north of ~40°N. The difference section highlights which regions of the water column have shown the largest changes in CFC-12 during the ~15 years between the occupation of the sections, and highlights the importance of LSW and AAIW over decadal scales in taking up and sequestering atmospheric gases into the interior of the ocean. The dramatic changes in the penetration of CFCs highlight the importance of the Atlantic for the ventilation of mid depth and abyssal waters on decadal time-scales.

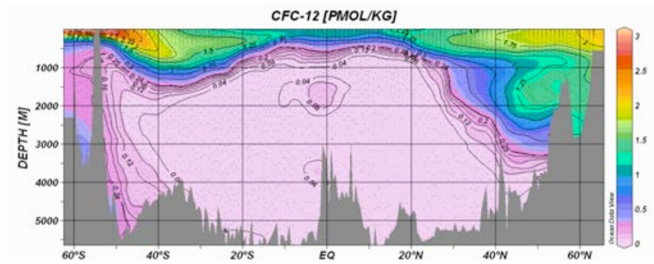

Figure 10. The observed CFC-12 concentrations from the 2005 A16S in the South Atlantic combined with those from the 2003 A16N cruise in 2003 in the North Atlantic.

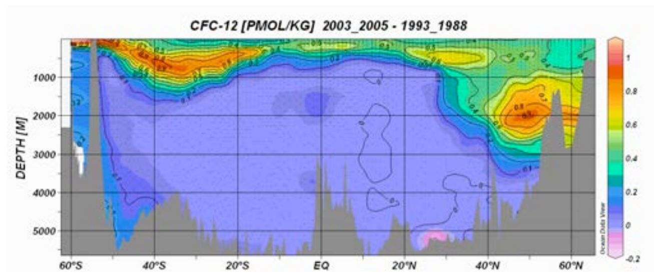

Figure 11. Cross section of the changes in dissolved CFC-12 concentrations along 20°W in the S. Atlantic between the 2003-2005 occupation and the 1988-1993 occupations.

Analysis of previous cruises

In FY 2005, G. Johnson continued analysis of data from the 2003 reoccupation of A16N and the three previous occupations, presented results at the American Geophysical Union Fall meeting, published a paper on Labrador Sea Water variability along 20°W over a 15-year period in Geophysical Research Letters, and submitted a paper on SubPolar Mode Water variability including analysis of regional substantial changes in oxygen and potential vorticity and their likely causes (ocean circulation) for publication.

Preparation for upcoming cruises

In addition in FY 2005, we also started preparing for the upcoming FY 2006 cruise from Papeete, Tahiti to Kodiak, Alaska via Honolulu, Hawaii on the R/V Thomas Thompson to reoccupy WOCE sections P16C and P16N. We built new 4-liter Niskin bottles for the 24-position frame for use in the heavy weather that the cruise will almost certainly encounter. We purchased some cruise supplies such as a new printer, CTD/O_2 supplies and cables, termination kits, standard seawater, and the like.

2. Document Ocean Carbon Sources and Sinks - Surface Water pCO_2 Measurements from Ships

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PROJECT SUMMARY

Determination of regional sources and sinks of carbon dioxide in the ocean are of critical importance to international policy decision making, as well as for forecasting long term climate trends. The oceans are the largest sustained sink of anthropogenic carbon and changes in this sink will be determined by monitoring regional and seasonal patterns of carbon uptake and release. In this project NOAA investigators and academic partners are outfitting research and commercial vessels with automated carbon dioxide sampling equipment to analyze the carbon exchange between the ocean and atmosphere. This task is coordinated at national level with the U.S. Carbon Cycle Science Program and its subcommittee on Ocean Carbon and Climate change (OCCC). We work with the International Ocean Carbon Coordination Project (IOCCP) for international coordination exercises. The IOCCP is a joint endeavor of the SCOR/IOC CO_2 panel and the IGBP-IHDP-WCRP Global Carbon Project. Collaborative efforts are underway to combine datasets in the Atlantic through a Memorandum of Understanding with the European Union project Carbo-Oceans. Pacific collaboration is established through the PICES working group 13. In addition there are one-on-one interactions with investigators in Iceland, France, the United Kingdom, Australia, New Zealand, and Japan on reciprocal data exchange and logistics support.

Documenting carbon sources and sinks relies critically on other efforts undertaken under sponsorship of the Office of Climate Observations (OCO) including implementation of the ship lines, and moored and drifting buoys. The surface water pCO_2 programs support climate services by providing knowledge and quantification of climate forcing of the radiatively important gas, carbon dioxide. The near-term focus is on completion of the Northern Hemisphere ocean carbon observing system to provide data for quantifying carbon dioxide sources and sinks over the coterminous United States through inverse modeling in collaboration scientists involved in the atmospheric CO_2 observing system.

The project is a partnership of AOML, AOML/GOOS, PMEL, LDEO of Columbia University, RSMAS of the University of Miami, and the Bermuda Biological Station for Research (BBSR). The partners are responsible for operation of the pCO_2 systems on the ships, auxiliary measurements, data reduction, and data management from all ships. The following ships have pCO_2 systems on them: NOAA ship *Ronald H. Brown*, NOAA ship *Ka'imimoana*, RVIB *Palmer*, cruise ship *Explorer of the Seas*, container ship *Columbus Waikato*, container ship *Skogafoss*, and container ship *Oleander*. Data from the project is being served from three websites that are linked and accessible from each site.
1. http://www.aoml.noaa.gov/ocd/gcc
2. http://www.pmel.noaa.gov/co2/uwpco2/
3. http://www.ldeo.columbia.edu/res/pi/CO2/
The final datasets are combined and sent to CDIAC for dissemination and archival.
All work follows established principles of monitoring climate forcing gases and biogeochemical cycles.

FY 2005 PROGRESS

Acquisitions, deployments and data return:

The following number of cruises with pCO_2 observations from research ships and VOS have been completed during the performance period. In most cases, these are the cruises for which data has been posted on the web.

- NOAA ship *Ka'imimoana*: 5 cruises servicing the TAO mooring in the Equatorial Pacific
- NOAA ship *Ron Brown*: 12 cruises in South Atlantic and Eastern Equatorial Pacific
- RVIB *Palmer*: 10 cruises in the Southern Ocean
- Royal Caribbean Cruise Line *Explorer of the Seas*: 72 cruises in the Caribbean Seas
- Container ship *Skogafoss: 11* cruises between Iceland and Boston
- Container ship *Oleander* (pCO_2 measurements commenced October, 2005)
- Container ship *Columbus Waikato*: 11 cruise be-

tween Long Beach Ca and Australia

The number of days at sea for the research ships was similar to the previous year. The tracks for 2004 - March 2005 are shown in Figure 1. Data return from the ships is over 90 %; the minimal data loss that did occur was due to instrument malfunction. Accurate records of malfunction are being kept such that we can get a better appreciation when systems need to be refurbished and to improve weak links. Although the systems are fully automated, all systems except that of the *Skogafoss* have a person on board for periodic checks. The *Skogafoss* operations have been problematic because of intermittent failures of the different component, and errors by the [untrained] persons servicing the system in ports.

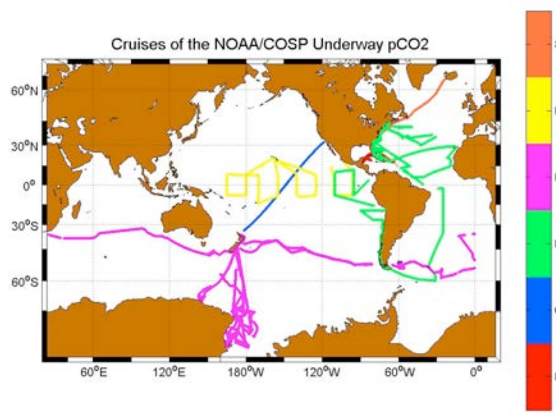


Figure 1. Lines occupied by the ships. The Skogafoss and Columbus Waikato tracks are monthly repeat occupations. The Explorer of the Seas are weekly occupations. The other tracks are one-time occupations during 2004 and beginning of 2005.

As part of the outreach efforts of pCO_2 on ships project, we found a manufacturer who will build autonomous pCO_2 systems for the community. A contractor Craig Neill at the University of Bergen built previous units. However, he could not continue producing and servicing them. An arrangement has been established in which General Oceanics Inc. of Miami Fl will build the systems patterned after the previous systems built by Craig Neill to assure uniformity of instrumentation. Scientists at AOML and RSMAS will oversee production of the first 10 units and provide product support. Participants in the project ordered four systems of the first production.

The outfitting of ships with systems continues with the recent completion of installation of a system on the *Oleander* that sails weekly between Newark and Bermuda. A second system has been installed on the R/V *Weatherbird II*. The systems were installed and will be maintained by the Bermuda Biological Station (Nick Bates).

There was a setback with outfitting a ship for the important trans-Atlantic transect (AX8) between the East Coast of the US and South Africa in that the ship was sold and its route was changed to the far-East after much of the installation was completed. The replacement ship used for the high density XBT work on this transect underwent a similar fate. The GOOS center is currently seeking another ship for the work.

A short summary of the efforts on each ship along with a small picture of the vessel are listed below:

NOAA ship *Ronald H. Brown*- AOML lead

Data Site:
http://www.aoml.noaa.gov/ocd/gcc/rvbrown_introduction.php
Number of cruises with data posted on web site (Jan 2004- March 2005): 12
Number of data points: ≈ 46 K

Causes for non-return: The underway pCO_2 system on the *Brown* enjoyed over a 90 % data return. At the end of 2004 there were periodic system failures due to unknown problems in communication between computer and pCO_2 instrument. The thermosalinograph on the *Brown* yielded poor data on several of the cruises complicating data reduction.

Description: In the beginning of 2004 the *Brown* was involved in studies in the Caribbean and off of West Africa. This was followed by a series of cruises off the coast of New England. In the late fall the ship performed the annual servicing of the Equatorial Pacific moorings and sailed south to start the CO2 CLIVAR repeat hydrography cruise A16S in the South Atlantic. A compilation of the cruises can be found in Appendix

A, Table A3). During A16S several other underway pCO_2 systems were tested and compared against our system. The comparison with the SAMI unit (Mike DeGrandpre, PI, U. Montana) and a system developed at the University of South Florida (R. Byrne, PI) are shown in figures 2 and 3.

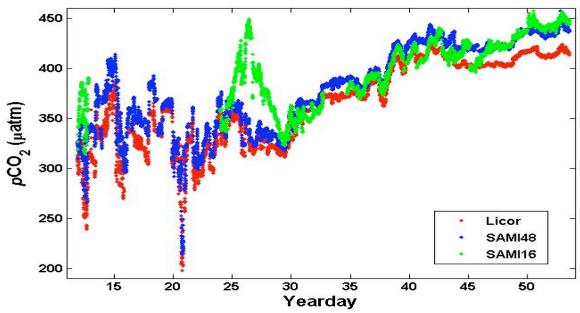


Figure 2. Comparison of new system design (a spectrophotometric shipboard SAMI system) funded by the Global Carbon Project of NOAA (GCC) with our analyzer on the cruise A16S. The two new prototype systems showed good high frequency resolution but experienced longer-term drift.

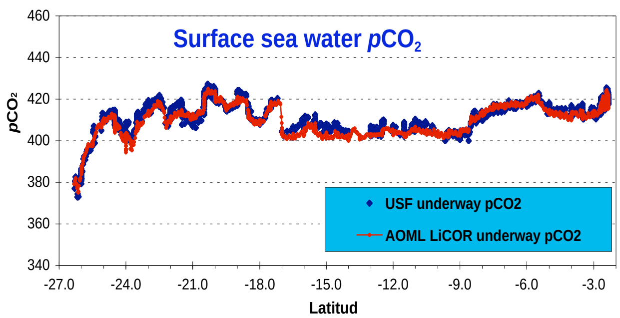


Figure 3. Comparison of new system design (a spectrophotometric shipboard multi-carbon species analyzer) funded by a NOAA appropriation to the University of S. Florida Center for Ocean Technology with our analyzer on the cruise A16S. The new prototype system showed good correspondence with our system. The USF system has higher temporal resolution due to the higher sampling rate (1-minute vs. 5-minutes).

NOAA ship *Ka'imimoana*- PMEL lead

Data Site: **http://www.pmel.noaa.gov/co2/uw**
Number of cruises: 5
Number of pCO_{2w} data points: 63,160
% Data return: 90%.

Causes for non-return: The underway pCO_2 system on the *Ka'imimoana* resulted in a 90 % data return during 2005. There were periodic system failures due to problems from water vapor removal. There were also problems associated with low water and gas flow. The thermosalinograph information must be integrated into the data files after the cruises which complicates data reduction.

Description: During 2005 the *Ka'imimoana* was involved in studies in the Equatorial Pacific between 95°W and 165°E (Figure 4). The cruise data can be obtained from our website located at: http://www.pmel.noaa.gov/co2/uw. A summary of the cruise results from November 1997 through August 2005 is shown in Figure 5. The results show weak seasonal and strong interannual variability of CO_2 fluxes from the oceans to the atmosphere. These results are described in detail in a manuscript recently submitted for publication by Feely et al., (submitted). The data will undergo further quality control testing by LDEO scientists before it is submitted to CDIAC for archiving.

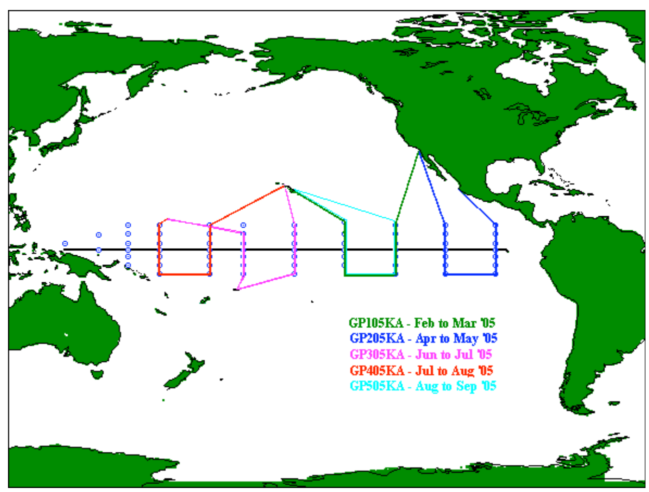


Figure 4. Ka'imimoana track lines which are operated twice per year.

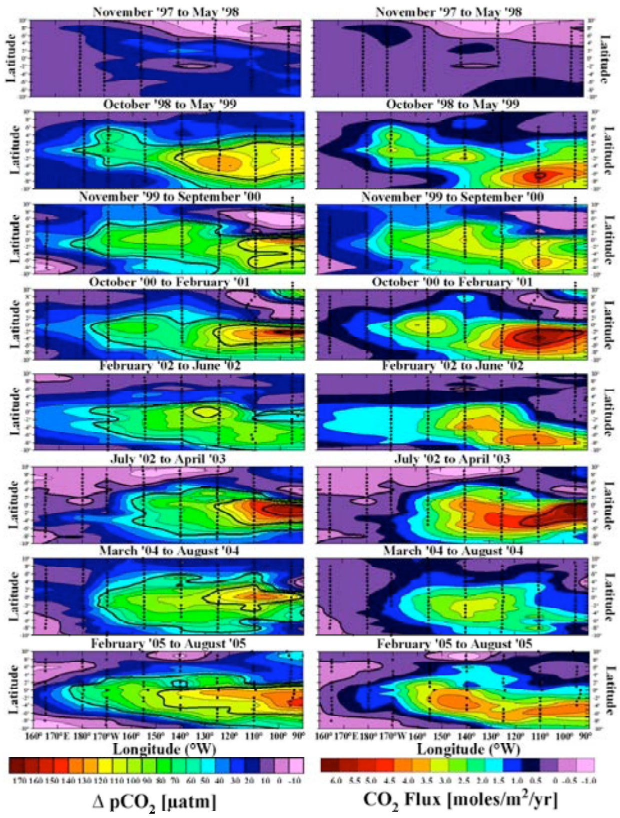


Figure 5. Time-Series of surface water pCO_2 levels in the tropical and subtropical Pacific Resulting from Ka'imimoana repeat observations from 1997 thru 2005.

RVIB *Palmer*- LDEO lead

Data Site:
http://www.ldeo.columbia.edu/res/pi/CO2/
Number of cruises: 10
Number of pCO_{2w} data points: ≈ 134K

Description:

The Lamont group is responsible for the acquisition of the surface water pCO_2 data aboard the RVIB Palmer. Our pCO_2 system has been upgraded with the support from NOAA for the past two years, and some new modifications are being added in order to make the system more stable and reliable. As the data are obtained, they are processed and added to our global database, which consists presently of about 1.9 million pCO_2 measurements in surface waters plus supplemental information including the SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration.

The locations of our data obtained aboard the RVIB *Palmer* since the beginning of this project in 2001 are shown in figure 6. The dates, location and number of measurements, which have been added to the web site during the present funding period, are listed in Appendix A, Table A1. A total of about 290,000 surface water pCO_2 measurements were processed and added during the first three years of this project (January, 2001 – December, 2003), and additional 134,000 have been processed and added to our database during this funding period, January 2004 through the end of April, 2005. The expeditions of the *Palmer* during 2004 included a circumnavigation of the entire Southern Ocean between approximate latitudes 35°S and 50°S. We also added several north-south transits of the Southern Ocean at several different longitudes. In 2005, *Palmer* resumed her normal operations in the New Zealand-Ross Sea areas after transiting from Chile in the early months of the year.

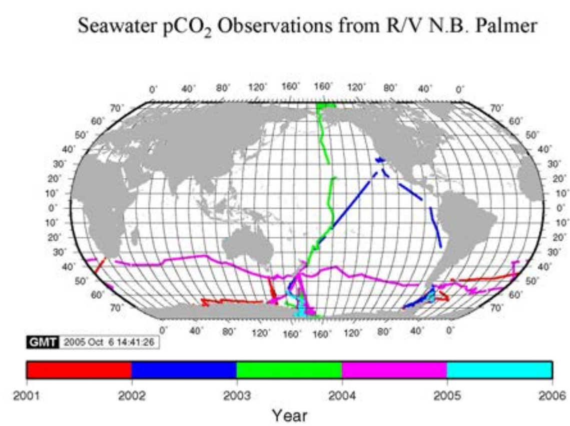


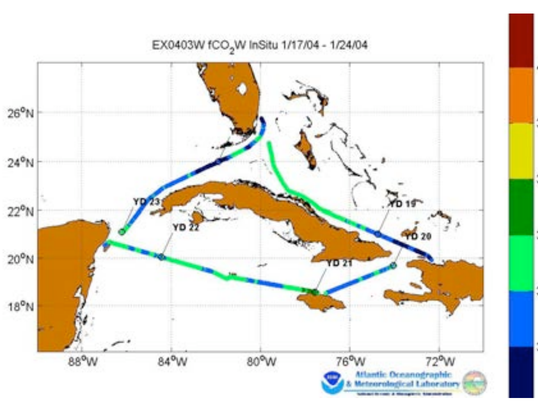
Figure 6. The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. Colors indicate the years when the measurements were made. Note, that our observations during 2004 include a circumnavigation of the entire Southern Ocean between approximate latitudes 35°S and 50°S. The 2005 observations are mostly in the New Zealand-Ross Sea and Drake Passage areas.

Further details can be found in the progress report from Dr. Takahashi, Appendix A

Cruise ship *Explorer of the Seas*-AOML lead

Data Site:
http://www.aoml.noaa.gov/ocd/gcc/explorer_introduction.php
Number of cruises *(Jan, 2004- August, 2005)****:*** 78
Number of pCO_{2w} data points: ≈ 128K
% Data return: >90 %

Causes for non-return: Some loss of data occurred because of automatic system shutoff due to stoppage of drain. The overflow of the equilibrator drains into the same holding tank as deck runoff. During periods of heavy rains the holding tanks overflow and the drain backs up. This causes an automatic shutoff of the pCO_2 system. A faulty circulation pump caused 1 weeks loss of data.
Description: The *Explorer of the Seas* alternates cruise tracks in the Eastern and Western Caribbean on a weekly basis (Figure 7). This yields excellent temporal and spatial coverage. The area has been used as a test bed to create flux maps utilizing remote sensing (see research highlights).



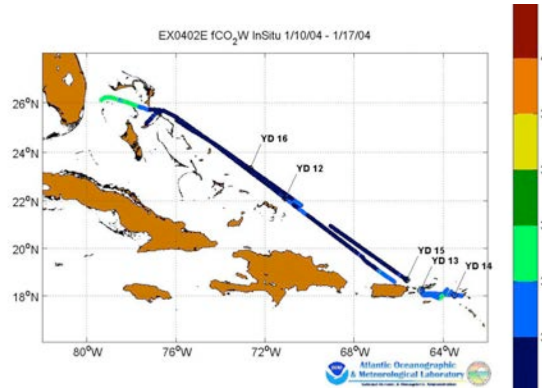


Figure 7. Eastern and Western Cruise Tracks of the Explorer of the Seas with surface water pCO_2 levels for January 2004.

Container Ship *Skogafoss*- AOML & RSMAS lead

Data Site:
http://www.aoml.noaa.gov/ocd/gcc/skogafoss_introduction.php
Number of cruises: 24
Number of pCO_{2w} data points*:* ≈ 75 K (≈ 24K points are on the on web but not final)
% Data return: 70 %

Causes for non-return: This has system run unattended or with untrained observers except for 3 cruises when AOML or RSMAS personnel were onboard. Data gaps have occurred for a variety of reasons, including failure by ship's personnel to open the seawater valves, leaks in the system that caused an automatic shutdown, a faulty leak sensing unit, and computer failure due to incorrect re-installation of a memory card. The problems have resulted in frequent trips by AOML and RSMAS personnel to the ship. We anticipate less loss of data in the coming year because of improved coordination with observers from France, an arrangement with the Icelandic Marine Institute to service the system in Reykjavik, and four transits with trained RSMAS/

AOML personnel.

Description: The *Skogafoss* sails between Iceland and Boston and covers a critical high latitude region that has been shown to be a large CO_2 sink. Large seasonal variations are observed as shown in figure 8. During the late spring pCO_2 values close to atmospheric levels are measured over the open ocean transect but low values are observed in the coastal region likely as a result of high biological productivity during this time. The transect in late fall shows lower values over the open ocean section but significantly higher values in the coastal regions.

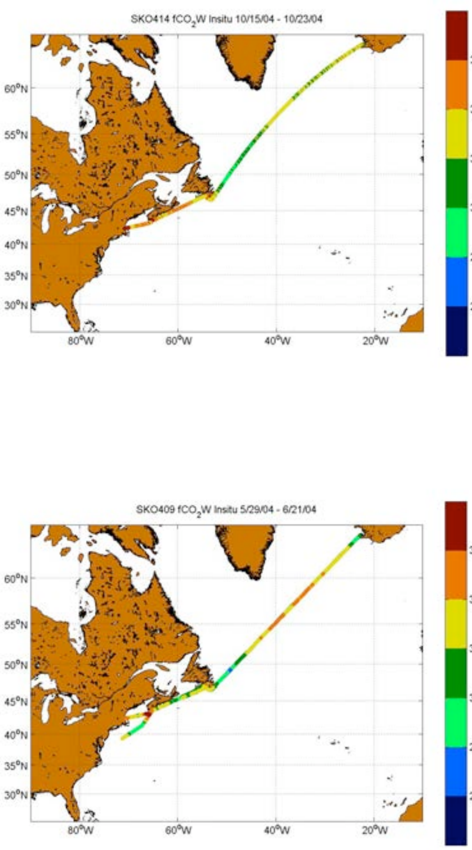


Figure 8. pCO_2 levels along the transect of the Skogafoss in May and October 2004 (figures from http://www.aoml.noaa.gov/ocd/gcc/skogafoss_data2004.php)

Container Ship *Oleander*- BBSR lead

Number of cruises*:* In operation October, 2005(anticipate 100 cruise over the next year)
Number of pCO_{2w} data points: n/a
% Data return: n/a

Installation Progress: The pCO_2 system has finally been installed on the MV *Oleander*. Due to port security, installation (and subsequent maintenance) of the system was not possible at the port of New Jersey. The short turnaround of the ship at Hamilton, Bermuda has made the installation process slow, but there will be sufficient time for maintenance every week. By the beginning of November 2005, the only remaining components required for completion is the installation of the GPS system and cable through the ship to the bridge. On the MV *Oleander*, the equilibrator is located in the Engine Room near the seawater system and TSG. It is located ~5' below the water line, requiring the equilibrator waste seawater to free drain into a waste reservoir, which in turn will be drained by a new pump back into the seawater line downstream of the tap off to the pCO_2 system. Care was taken with the installation that there is no interference with the TSG system. The seawater and atmospheric pCO_2 data will also be served at the following site
(http://www.bbsr.edu/Labs/co2lab/vos.html).

Description: The MV *Oleander* crosses weekly between New Jersey and Hamilton, Bermuda. Given the ~100 crossings a year, this gives excellent temporal and spatial coverage of the North Atlantic subtropical gyre, Gulf Stream, middle Atlantic Bight and coastal zone. The MV Oleander transits the region of Subtropical Mode Water (STMW) formation during the winter southeast of the Gulf Stream, and the highly productive coastal zone of the Eastern Seaboard.

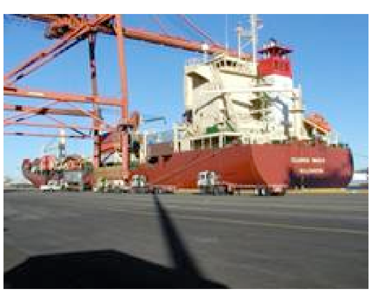
R/V *Weatherbird II*- BBSR lead

***Number of cruises**:* Anticipate 150-220 ship days in 2006
Number of pCO_{2w} data points: n/a
% Data return: n/a

Installation Progress: A pCO_2 system has been installed on the R/V *Weatherbird II* (BBSR's UNOLS research vessel, based in Bermuda) in October 2005. Although not directly part of the NOAA VOS program, pCO_2 data from the R/V *Weatherbird II* will be directly fed into this project. The data will also be served at the following site (http://www.bbsr.edu/Labs/co2lab/vos.html).

Description: The R/V *Weatherbird II* operates in the North Atlantic Ocean (zone NA6), servicing four oceanographic time-series (e.g., Bermuda Atlantic Time-series Study, Hydrostation S, Bermuda Testbed Mooring, Ocean Flux Program) and other research projects. This data stream provides groundtruthing pCO_2 datasets for the subtropical gyre of the North Atlantic Ocean. In early 2006, the pCO_2 system will be transferred to BBSR's new ship (the renamed 168' Seward Johnson II), and we anticipate 200-220 ship days per year. The pCO_2 system for both vessels will be maintained at BBSR's dock before and after each cruise, depending on schedule.

Container ship *Columbus Waikato* - PMEL lead



Number of cruises: *11*
Number of pCO_{2w} data points: 153049
% Data return: *96*

Causes for non-return: The underway pCO_2 system on the *Columbus Waikato* resulted in a 96 % data return during 2005. There were minor system failures due to problems associated with water vapor removal.

Description: During the fall of 2004 and 2005 the *Columbus Waikato* was involved in studies in the tropical and subtropical Pacific (Figure 9). This research is done in collaboration with Drs. Paul Quay of the University of Washington and Bronte Tilbrook of the CSIRO in Hobart, Australia. In addition to supporting our underway pCO_2 measurements, they are also collecting samples for carbon isotope measurements (Quay) and DIC and nutrients (Tilbrook). For this reason, we have combined resources to place ship riders on each of the cruises. They maintain the underway systems and collect the discrete samples. The cruise data can be obtained from our website located at**:** http://www.pmel.noaa.gov/co2/uw. A summary of the cruise results from February 2004 thru September 2005 is shown in Figure 10. The results show strong seasonal variability of CO_2 fluxes in the subtropics. These results are described in the AGU/ASLO abstract by Cosca et al., (submitted). The data will undergo further quality control testing by LDEO scientists before it is submitted to CDIAC for archiving.

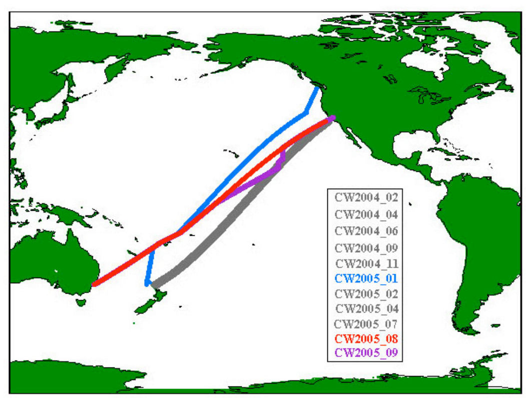


Figure 9. Cruise Tracks of the Columbus Waikato for 2004 and 2005.

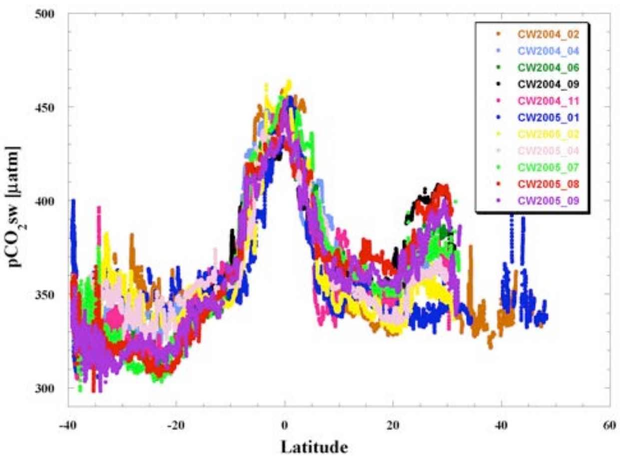


Figure 10. Time-Series of surface water pCO_2 levels in the tropical and subtropical Pacific Resulting from Columbus Waikato repeat observations during 2004 and 2005.

Adherence to monitoring principles

The efforts of the NOAA VOS pCO_2 group have met the important monitoring principle of uniform instrumentation with a quantifiable accuracy. All systems are calibrated with standards that are traceable to the WMO scale. The first units were delivered in the summer of 2003, within a year of receipt of program funding. In FY05 one additional VOS ships was outfitted (the *Oleander*). We are actively involved in assuring uniform instrumentation, through interactions with the manufacturer GO, uniform operating protocol, and uniform data reduction procedures.

Data management and dissemination:

An important part of the VOS effort is to disseminate quality controlled data to the community at large in an expedient fashion. The LDEO group, in close interaction with the data acquisition groups, oversees shipboard quality control so that the quality of data and consistency is monitored for the whole group. This close coupling of the data acquisition with data processing/evaluation and interpretation will guarantee high quality field observation data. The LDEO group also coordinates submission of the collated data to the underway pCO_2 data center at CDIAC for community access. They participate in data interpretation with the data acquisition groups. This will facilitate discussions about data quality and insure that the observationists will be engaged in the interpretation processes.

Data obtained from the research ships are currently served from the institution responsible for the measurement. The data from the research ships are currently being ingested by the LDEO group for the release to CDIAC. This component was added to the LDEO data management responsibilities in the project.

CDIAC has just implemented a Live Access Server (LAS) for the data with funding from a companion effort. The LAS at http://cdiac3.ornl.gov/underway/servlets/dataset is being populated. Investigators, and the oceanographic community use the data extensively. This data is also used for national and international assessments such as the IPCC.

Good progress has been made to post the pCO_2 data on the web sites. A listing of current updates is provided below. A major change has been the formatting. Based on a meeting in Japan sponsored by IOCCP in January 2004, an international standard of data formatting was adapted for this program. AOML and PMEL have reformatted most of their data to this format over the past year.

Latest updates (as of September 2005):

http://www.aoml.noaa.gov/ocd/gcc

Brown:	March 2005
Explorer:	August 2005
Skogafoss:	November 2004

http://www.pmel.noaa.gov/co2/uwpco2/

Ka'imimoana:	June 2004
Columbus Waikato:	July 2004

http://www.ldeo.columbia.edu/res/pi/CO2/

Palmer	March 2005
Gould	March 2005

In several instances, several years of data have been posted over the last year. Further details on data management can be found in the progress report from Dr. Takahashi, Appendix A

Problems:

The late receipt of funds from NOAA, in particular for our academic colleagues slowed down the work schedule. Access to ships has been difficult at times, which has hampered installation efforts, particularly for the MV *Oleander*. In this instance, installation of the pCO_2 system on the MV *Oleander* in the port of Newark became very problematic (due to port security and uncertain berthing locations due to the relatively small size of the vessel). At the request of the owners and captain, installation has shifted to Hamilton, Bermuda. Routine data downloads from the *Skogafoss* have sometimes not occurred in port because personnel of the GOOS/SEAS group, who are partners in this effort, were not available. The problems is associated with lack of personnel resources have been addressed by including needed personnel in the budgeted request.

Systems on the ships have worked very well, except for the *Skogafoss*. The *Skogafoss* is the only ship without a person on board for periodic checks. The *Skogafoss* operations have been problematic because of intermittent failures of the pumped waste water system that automatically shuts the system down to avoid flooding of the bilges. Never-the-less data has been obtained on 70 % of the ship transects. On the MV *Oleander*, the equilibrator (located in the Engine Room and ~5' below the water line) will free drain into a waste reservoir, which in turn will be drained by a new pump back into the seawater line downstream of the tap off to the pCO_2 system. A new equilibrator was placed on the *Explorer of the Seas.* We have determined that a ship rider is required to attend the underway system on the *Columbus Waikato* because of the difficulties associated with the language differences between the scientists and the crew. We found that by working with scientists from the University of Washington, CSIRO in Hobart and the University of Southern California we can accomplish that task, provided we continue our subcontract with the University of Southern California.

Project costs:

Anticipated- Anticipated data costs include data reduction, dissemination, interpretation, and data archiving. Anticipated instrument costs include design, purchase, installation and maintenance.

Unanticipated- Unanticipated costs included higher maintenance costs, instrument development costs, and personnel and travel costs to repair and maintain systems.

Logistical considerations- Work on the research ships proceeded as planned. The *Brown* was used for the several coastal cruises in the NE Atlantic that will provide important baseline considerations for the anticipated coastal carbon program.

RESEARCH HIGHLIGHTS

1. It is widely recognized that robust methods to interpolate CO_2 measurements in time and space are needed to produce CO_2 flux maps from measurements along a line. Publications by Cosca *et al.* (2003) and Feely *et al.* (2004) for the Equatorial Pacific and Olsen *et al.* (2003) for the Caribbean Seas show how temperature can be utilized to produce regional flux maps. The algorithms are area specific but show a robust predictive capacity and provide a way to utilize remote sensing to produce flux maps with high spatial and temporal resolution. The data used to create the algorithms were obtained on the ships funded under this effort. Examples of application of these procedures are listed below.

2. Air-Sea CO_2 fluxes in the Caribbean: Air-sea fluxes in the Caribbean Sea are determined from 2002-2004 based on data from an automated system onboard the cruise ship Explorer of the Seas. The partial pressure of CO_2 in seawater, pCO_{2sw}, and values are used to develop algorithms of pCO_{2sw} based on sea surface temperature (SST) and position. Regressions are applied to assimilated SST data and remotely sensed winds on a 1˚ by 1˚ grid to estimate the fluxes on weekly timescales in the region. The positive relationship between pCO_{2sw} and SST is lower that the iso-chemical trend suggesting counteracting effects from biological processes. The relationship varies systematically with location with a stronger dependence further south. Furthermore, the southern area shows significantly lower pCO_{2sw} in the fall compared to the spring at the same SST, which is attributed to differences in salinity. The annual algorithms for the entire region show a slight trend between 2002 and 2004 suggesting an increase of pCO_{2sw} over time. This is in accord with the increasing pCO_{2sw} due the invasion of anthropogenic CO_2. The annual fluxes of CO_2 yield a net invasion of CO_2 in the ocean that ranges from -0.04 to -1.2 mol m^{-2} yr^{-1} over the three years. There is a seasonal reversal in the direction of the flux with CO_2 entering into the ocean during the winter and an evasion during the summer. Year-to year differences in flux are primarily caused by temperature anomalies in the late winter and spring period resulting in changes in invasion during these seasons (Figure 11). (Reference: Wanninkhof et al. 2005).

3. As part of our continuing effort to understand decadal changes in the carbon fluxes of the equatorial Pacific, we developed seasonal and interannual fCO_2-SST relationships from shipboard data that were applied to high-resolution temperature fields deduced from satellite data to obtain high-resolution large-scale estimates of the regional fluxes. The data were gathered onboard research ships from November 1981 through June of 2004. The data were collected during repeat transects of the equatorial Pacific between 95°W and 165°E, and included five El Niño periods (1982–1983, 1986–1987, 1991–1994 and 1997–1998 and 2002–1903) and three La Niña

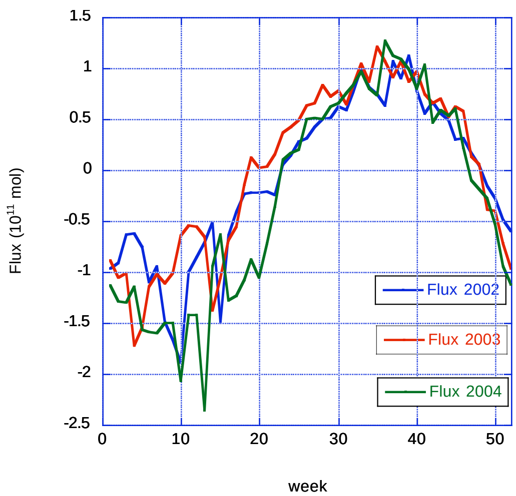


Figure 11. Weekly flux maps for the Caribbean Sea for 2002-2004 based on observations of the Explorer of the Seas and algorithms using remotely sensed SST (Wanninkhof et al., 2005).

periods (1988–1989, 1995–1996 and 1998–2000). Data were collected during the warm boreal winter-spring season (January through June) and during the cooler boreal summer-fall season (July through December) of each year making it possible to examine the interannual and seasonal variability of the fCO_2-SST relationships. A linear fit through he data sets yields an inverse correlation between SST and fCO_2, with both interannual and seasonal differences in slope. In particular, the results indicate a strong interannual (ENSO) note, spell out ENSO, PDO and weaker seasonal variability. There is also a slight increase (~27%) in the out-gassing flux of CO_2 after the 1997–1998 PDO mode shift. Most of this increase is due to increase in wind speeds after the spring of 1998. These increases are consistent with the recent rebound of the shallow water meridional overturning circulation in the tropical and subtropical Pacific after the PDO shift. (Reference: Feely et al., 2005)

4. Using the observations made since the 1970's we have investigated increases in pCO_2 in surface water in the North Pacific Ocean. In 19 areas that are located in the open North Pacific, the surface water pCO_2 values have been increasing at a rate similar to the mean atmospheric CO_2 increase of about 1.5 ppm/yr. Although surface waters are out of equilibrium with atmospheric CO_2 because of the seasonal swing of SST, biological production and deep-water upwelling, the ocean surface waters appear to take up CO_2 from the air keeping up with the atmospheric CO_2 increase. In contrast, in four areas located near and within the Bering and Okhotsk Seas, the surface water pCO_2 have been decreasing with time, in spite of the fact that surface water temperatures have been increasing. This may be attributed to an increase in photosynthesis in the high latitude northern North Pacific, that have been reported by Gregg et al. (2003) on the basis of remote-sensed ocean colors. (Reference: Takahashi et al., 2005)

5. We have initiated plans with General Oceanics to supply pCO_2 systems for use in this program. The systems are patterned after the Neill pCO_2 system and six systems are presently under construction. Dr. Denis Pierrot and Mr. Kevin Sullivan are overseeing the construction, and the calibration of this system. Commercial systems should be available next year.

APPENDIX

Underway CO_2 Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program

Taro Takahashi

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY

1. INTRODUCTION:

This report describes the progress made during the period May, 2004 through September 2005 under the two NOAA grants which are ending August 31, 2005: NA030AR4310043 entitled “Underway CO_2 Measurements on the NOAA Ships Ka’imimoana and Ron Brown, the RVIB Palmer and the Explorer of the Seas” and NA16GP2001 entitled “Collaborative Research: Initial Steps Toward a Global Surface Water pCO_2 Observing System, Quality Control and Processing of Data”. No-cost extension for these grants have been requested. After September 1, 2005, these two grants are combined to one grant NA03OAR432179 which is entitled “CICAR-Underway CO_2 measurements aboard the RVIB Palmer and data management of the global VOS program”.

2. PROJECT OBJECTIVES:

The sea-air net flux of CO_2 is governed by the pCO_2 difference between surface ocean water and the overlying atmosphere and by the gas transfer rate across the sea-air interface. The former depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), and the latter is controlled mainly by ocean-atmosphere interactions including wind-induced turbulence above and below the interface. The primary objective of this proposed investigation is to determine the space-time distribution of the sea-air pCO_2 difference. In conjunction with CO_2 gas transfer coefficients which are being improved by other scientific groups, a reliable net sea-air flux of CO_2 estimate over regional to global scales can be obtained using improved sea-air pCO_2 difference data. The results will give us an improved understanding of geographical and interannual variability of the sea-air CO_2 transfer flux. .

For our proposed work, we operate a semi-automated surface water pCO_2 system aboard the RVIB *Nathaniel Palmer* with vital operational assistance from the Raytheon Polar Support group. Since RVIB *Palmer*, an ice-breaking research vessel, is one of the few research ships which are operated in high latitude areas of the Southern Ocean even during winter months, our CO_2 program aboard this vessel allows us to make observations in hostile environments of the high latitude oceans, where deep and intermediate water masses are formed. Although the *Palmer* spends a large fraction of year in the Weddell and Ross Seas, Antarctica, she has taken a few long trans-oceanic cruises over warmer oceans during the past three years. Therefore, in addition to seasonal and interannual observations over the high latitude Southern Oceans, we have been able to make measurements along long transects over the central Pacific from Antarctica to the Bering and Arctic Seas during the previous funding period, as well as along a complete circumpolar path around the Southern Ocean during the current funding period (see Fig. 1). We continue to acquire the surface ocean pCO_2 and associated SST and salinity data aboard the RVIB *Palmer* during this coming investigation period.

Our proposed work is a part of a consortium of investigators who operate their respective pCO_2 systems aboard other research and commercial vessels. The consortium includes the following groups: Richard Feely and his PMEL/NOAA group investigate mainly the equatorial Pacific aboard the NOAA ships; Rik Wanninkhof and his group at AOML/NOAA are primarily responsible for measurements over the Atlantic Ocean; Nick Bates of the Bermuda Biological Station for Research makes measurements in the western North Atlantic between Bermuda and N. America; Frank Millero and his group at the University of Miami investigate coastal waters and the Caribbean Sea. Pooling of the data among the participants will allow us to cover a large part of the global oceans. The data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany and France, are being processed into a single format at the Lamont-Doherty Observatory, and are made accessible to the participants via our web site (www.ldeo.columbia.edu/CO2). In addition, we have initiated the transfer of the data to the Carbon Dioxide Information and Analysis Center (CDIAC) at the Oak Ridge National Laboratory, for the permanent archive and ready access to the public. Research papers on the interpretation of the data are being written with collaborating researchers.

3. PROGRESS TO DATE:

3-a) Field Program aboard the RVIB *Palmer*:

The Lamont group is primarily responsible for the acquisition of the surface water pCO_2 data aboard the RVIB Palmer. Our pCO_2 system has been upgraded with the support from NOAA for the past two years, and some new modifications are being added in order to make the system more stable and reliable. As the data are obtained, they are processed and added to our global database, which consists presently of about 1.9 million pCO_2 measurements in surface waters plus supplemental information including the SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration.

The locations of our data obtained aboard the RVIB *Palmer* since the beginning of this project in 2001 are shown in Figure. A1. The dates, location and number of measurements, which have been added to the web site during the present funding period, are listed in Table A1. A total of about 290,000 surface water pCO_2 measurements were processed and added during the first three years of this project (January, 2001 – December, 2003), and additional 134,000 have been processed and added to our database during this funding period, January 2004 through the end of April, 2005. The expeditions of the *Palmer* during 2004 included a circumnavigation of the entire Southern Ocean between approximate latitudes 35°S and 50°S. We also added several north-south transits of the Southern Ocean at several different longitudes. In 2005, *Palmer* resumed her normal operations in the New Zealand-Ross Sea areas after transiting from Chile in the early months of the year.

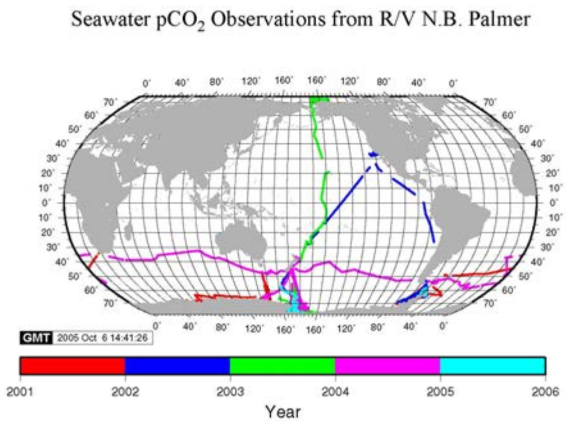


Figure A1- The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. Colors indicate the years when the measurements were made. Note that our observations during 2004 include a circumnavigation of the entire Southern Ocean between approximate latitudes 35°S and 50°S. The 2005 observations are mostly in the New Zealand-Ross Sea and Drake Passage areas.

3-b) Upgrading of the pCO_2 System aboard the RVIB Palmer:

In the two previous grants, we requested funds for replacing the old system, which had been in use since 1992. The old system has been completely replaced with a new system, which includes many improved features for operational ease and reliability. Additionally, an improved software will be installed by Tim Newberger during the next few months. A no-cost extension of the grant has been requested for this purpose.

3-c) pCO_2 Data Processing and Management:

The Lamont group is responsible for quality control (QC) and management of the surface water pCO_2 data acquired by the members of the VOS consortium, so that the participants of the VOS program are able to access the data which are listed in an uniform format. For this purpose, we have established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a set period agreed on by the PIs, and will be sent to the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, for the permanent archiving and distribution to the public. The formats for the data and the metadata are being formulated by Stew Sutherland of LDEO and Alex Kozyr of CDIAC.

3-d) Data from the NSF's LTRE Program in the Drake Passage Area:

As a part of the VOS program, we processed and added to our database 38 cruises from the R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program. For most of the time, the Gould transits across the Drake Passage, but for two legs, she sailed from Chile to Louisiana and return (Fig. 2). Since part of the southbound transit was within the Exclusive Economic Zones of South American Countries, observations were not allowed. During the present reporting period, about 61,000 new surface water pCO_2 data have been added to our database. A total of 215,000 surface water pCO_2 data representing observations made during March 2002 through June 2005 has been contributed from the LTRE program. The locations and year of the measurements are shown in Fig. A2, and the number of the measurements and the dates of each leg are listed in Table A2.

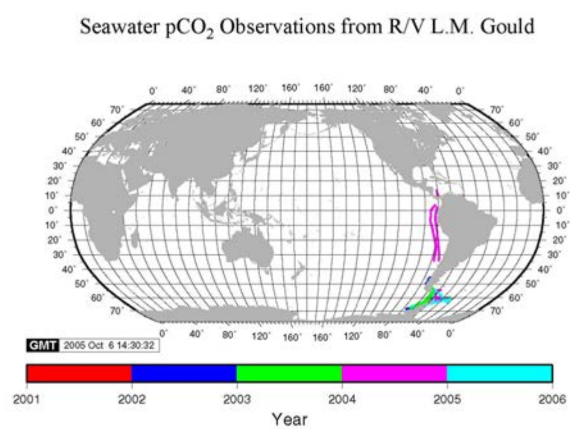


Figure A2 – The locations of the surface water pCO_2 measurements obtained aboard the RV Gould during this project, January, 2001 through May 2004. The years of the measurements are color-coded.

CRUISE DESIGNATION	PROJECT NAMES	DATES	NO. OF PCO_2 OBS.
NBP 01/1	East Antarctic Margin	30 Jan - 20 Mar 2001	12,300
NBP 01/2	South West Pacific	01-19 Apr 2001	6,541
NBP 01/3	SO-GLOBEC	23 Apr - 06 Jun 2001	20,446
NBP 01/4	SO-GLOBEC	21 Jul - 01 Sep 2001	14,960
NBP 01/5	Antarctic Peninsula	07 Sep - 26 Oct 2001	27,312
NBP 01/6	SO-GLOBEC	09 Nov- 01 Dec 2001	10,317
NBP 01/7	Antarctic Peninsula	05 Dec 01 - 12 Jan 02	22,627
NBP 02/1	Antarctic Peninsula	18 Jan - 04 Mar 02	24,542
NBP 02/2	GLOBEC III	09 Apr - 21 May 2002	25,327
NBP 02/4	GLOBEC IV	31 Jul - 09 Sep 2002	29,640
NBP 02/5	Transit along W. South America	23 Sep - 19 Oct 2002	8,317
NBP 02/6	USCG Inspection	30 Oct - 08 Nov 2002	6,732
NBP 02/7	Reconst. of Paleo S. Pac.	10 Nov - 06 Dec 2002	5,702
NBP 02/9	ANSLOPE, from Lyttleton to McMurdo	11 Dec 2002 - 03 Jan 2003	6,925
NBP 03/1	Ross Ice Shelf Survey	5 - 30 Jan 2003	8,062
NBP 03/1A	Ross Sea Research	2-20 Feb 2003	7,227
NBP 03/2	Ross Sea Research	25 Feb - 09 Apr 2003	13,897
NBP 03/4	Transit N.Z to Alaska	23 May - 02 Jul 2003	9,864
NBP 3/4A	Alaska North Slope	06 Jul - 18 Aug 2003	17,136
NBP 03/5	Southern Ocean near 175E	26 Oct - 13 Dec 2003	7,427
NBP 3/5A	Ross Sea Research	18 Dec 2003 - 02 Jan 2004	4,501
TOTAL 2001-2004 (Previous reporting periods)			***289,802***
NBP 04/1	Western Ross Sea	20 Jan - 19 Feb 2004	12,299
NBP 04/2	ANSLOPE III	26 Feb - 11 Apr 2004	17,708
NBP 04/3	Transit New Zealand to Chile	16 Apr - 12 May 2004	9,463
NBP 04/4	Transit Chile to South Africa	18 May - 19 Jul 2004	22,755
NBP 04/6	Transit South Africa to New Zealand	27 Jul - 20 Aug 2004	14,227
NBP 04/8	ANSLOPE IV	06 Oct - 10 Dec 2004	21,958
NBP 04/9	Antarctic Research	15 Dec 2004 - 23 Jan 2005	14,443
NBP 05/1	Transit McMurdo to Chile	17 Jan - 16 Feb 2005	5,736
NBP 05/1B	Transit New Zealand to Chile	03 Mar - 24 Mar 2005	7,494
NBP 05/2	Tidewater Glaciers	31 Mar - 24 Apr 2005	8,235
NBP 05/5	Antarctic Research	23 Jun - 14 Jul 2005	In Prep.
TOTAL 2004-2005 (Current Reporting Period)			***134,368***

Table A1 – List of the RVIB N. B. Palmer expeditions and the number of surface water pCO_2 measurements obtained since the inception of this project in 2001 through May, 2005.

Cruise No.	Project Name	Dates	No. Obs.	Annual Total
2002				
02/1	Antarctic Penninsula	07 - 18 Mar 02	2731	
02/2	Palmer Shuttle	22 Mar - 02 Apr 02	1879	
02/3	GLOBEC III	07 Apr - 20 May 2002	8659	
02/4	Palmer Shuttle	21 Jun - 22 Jul 2002	4815	
02/5	GLOBEC IV	29 Jul - 18 Sep 2002	6787	
02/6	Palmer Shuttle	23 Sep - 07 Oct 2002	2332	
02/8	Open Cape Shirreff	03 Nov - 17 Nov 2002	3137	
02/9	Scotia Arc GPS Project	23 Nov - 23 Dec 2002	8209	**38,549**
2003				
03/1	LTER	31 Dec 2002 - 08 Feb 2003	13831	
03/2	GLOBEC	13 Feb - 07 Mar 2003	4167	
03/2	Palmer Shuttle	12 Mar - 29 Mar 2003	5721	
03/4	Biological Research	05 Apr - 07 May 2003	9334	
03/4A	Biological Research	10 May - 05 Jun 2003	4629	
03/5	Palmer Shuttle	15 Jun - 29 Jun 2003	2618	
03/5A	Palmer Shuttle	15 Aug - 04 Sep 2003	5774	
03/6	Palmer Shuttle	23 Sep - 06 Oct 2003	2495	
03/7	Palmer Shuttle	10 - 22 Oct 2003	3450	
03/8	Palmer Shuttle	07 - 18 Nov 2003	3758	
03/9	Antarctic Penn Research	23 Nov - 29 Dec 2003	12288	**68,065**
2004				
04/1	Antarctic Penn Research	01 Jan - 07 Feb 2004	12556	
04/2	Antarctic Penn Research	12 Feb - 24 Mar 2004	14222	
04/3	Antarctic Penn Research	28 Mar - 12 Apr 2004	2100	
04/4	Antarctic Penn Research	16 Apr - 10 May 2004	5510	
04/5	Antarctic Penn Research	14 - 24 May 2004	3797	
04/6	Palmer Shuttle	30 May - 09 Jun 2004	2609	
04/7	Palmer Shuttle	13 - 27 Jun 2004	2835	
04/8	Transit Chile to Louisiana	06-16 Jul 2004	3849	
04/10	Transit Louisiana to Chile	25 Aug - 12 Sep 2004	4539	(Inside EEZ)
04/11	Palmer Shuttle	25 Sep - 12 Oct 2004	3165	
04/12	Palmer Shuttle	17 - 30 Oct 2004	2091	
04/13	Palmer Shuttle	08 - 18 Nov 2004	4014	
04/14	Palmer Shuttle	24 Nov - 31 Dec 2004	10916	**72,203**
2005				
05/1	LTER Palmer Penn.	31 Dec 2004 - 05 Feb 2005	14091	
05/2	Paleohistory of Larsen Shelf	11 Feb - 12 Mar 2005	11411	
05/3	Palmer Shuttle	15 Mar - 28 Mar 2005	2398	
05/4	Acoustic Census in W Antarc.	02 Apr - 15 Apr 2005	1377	
05/5	Evolution of Antarctic Fishes	20 Apr - 12 May 2005	3674	
05/6	Evolution of Antarctic Fishes	18 May - 09 Jun 2005	3126	
05/7	Tracers, Bio and Gas Exch.	13 Jun - 28 Jun 2005	in prep	
05/8	Hazardous Waste Pickup	03 Jul - 31 Jul 2005	in prep	
05/9	Palmer Shuttle	16 Aug - 02 Sep 2005	in prep	**36,076**
	Grand Total			**214,893**

Table 2 – List of the R/V Laurence M. Gould expeditions and the number of surface water pCO_2 observations added to the VOS database since the inception of this project in 2002.

SHIP	CRUISE NO.	PROJECT NAME	DATES	pCO_2 Obs.
AOML/NOAA				
Ron Brown	RB-04-01	NTAS Mooring	12-24 Feb 2004	2,301
Ron Brown	RB-04-02A	Saharan Dust Leg A	29 Feb-15 Mar 2004	2,539
Ron Brown	RB-04-02B	Saharan Dust Leg B	17-26 Mar 2004	1,776
Ron Brown	RB-04-03	Windward Passage	29 Mar-12 Apr 2004	2,668
Ron Brown	RB-04-04A	Ocean Expl. Transit	29 Apr-03 May 2004	612
Ron Brown	RB-04-04B	Ocean Expl. Mount.	08-24 May 2004	2,818
Ron Brown	RB-04-05	Ocean Expl. Titanic	27 May-10 Jun 2004	2,486
Ron Brown	RB-04-06	NURP Deep Sea Corals	17-28 Jun 2004	2,032
Ron Brown	RB-04-07A	New England Air Qual	05-23 Jul 2004	3,347
Ron Brown	RB-04-07B	New England Air Qual	26 Jul - 12 Aug 2004	2,920
Ron Brown	RB-05-01A	CLIVAR A16S Trans.	20 Dec 04 - 05 Jan 05	1,332
Ron Brown	RB-05-1B	Clivar A16S	11 Jan - 22 Feb 2005	7.829
Subtotal				**32,363**
Expl. Seas*	EX0401	Weekly Cruises in Caribbean Sea and Western Trop. Atlantic	From 02 March 2002 through 03 April 2005	
		2002: 30 Files		39,262
		2003: 39 Files		76,322
		2004: 50 Files		82,025
Expl. Seas	EX0517	2005: 28 Files		44,834
Subtotal				**242,443**
PMEL/NOAA				
Ka'imimoana	KA2004_1	TAO-TOGA Array	27 Mar-24 Apr 2004	3,696
Ka'imimoana	KA2004_2	TAO-TOGA Array	28 Apr-31 May 2004	3,589
Ka'imimoana	KA2004_3	TAO-TOGA Array	18 Jun-14 Jul 2004	2,999
Ka'imimoana	KA2004_4	TAO-TOGA Array	12 Jul-15 Aug 2004	3,466
Subtotal				**13,742**

*/ Cruise Ship "*Explorer of the Seas*"

Table A3 - Surface water pCO_2 data received from the AOML/NOAA and PMEL/NOAA groups for quality control and archiving.

3-e) Data from the NOAA's AOML and PMEL:

During the current funding period, we have received a large number of surface water pCO_2 data from the AOML and PMEL groups of NOAA. These data have been examined at Lamont and added to our database. The cruise designations, dates and the number of pCO_2 measurements obtained are listed in Table A3. Since the location map for these NOAA data are shown in the AOML and PMEL CO_2 websites, they are not duplicated here. A total of about 275,000 pCO_2 observations has been received from AOML/NOAA (R. Wanninkhof PI), quality-controlled at Lamont and added to our database. These data include about 32,000 pCO_2 observations obtained in the Atlantic aboard the R/V *Ron Brown* during one year period (February, 2004 – February, 2005) and 242,500 pCO_2 observations made aboard the Cruise Ship "*Explorer of the Seas*" in the Caribbean Sea and the western tropical Atlantic areas from March, 2002 to April, 2005.

Additional 13,750 pCO_2 measurements have been received from PMEL/NOAA (R. A. Feely and C. Cosca) and added to our database after quality control. These data have been obtained aboard the *Ka'imimoana* between March and August 2004.

These NOAA data will be transmitted to the CDIAC for archiving and public access.
Table A3 - Surface water pCO_2 data received from the AOML/NOAA and PMEL/NOAA groups for quality control and archiving.

3-f) Data Analysis and Synthesis:

In collaboration with researchers, we have analyzed the data and the results have been published or submitted for publications in scientific journals. A partial list of 2004-2005 publications and submissions relevant to the effort are listed in the publication section and provided below.

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3. High Resolution Ocean And Atmosphere pCO_2 Time-Series Measurements

Christopher L. Sabine[1], Francisco Chavez[2], Nicholas Bates[3]

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PROJECT SUMMARY

1.1 General Overview

The fossil fuel carbon sources and the growth of atmospheric CO_2 are reasonably well known based on economic reconstructions and atmospheric monitoring (Prentice *et al.*, 2001). A number of complementary, albeit indirect, means have been proposed for partitioning the long-term net carbon sink between ocean and land reservoirs, producing generally similar results for the global net ocean uptake of ~2 Pg C yr^{-1}. These include global ^{13}C budgets for CO_2 (Quay *et al.*, 1992; Tans *et al.*, 1993; Heimann and Maier Reimer, 1996; Quay *et al.*, 2003), data based estimates of anthropogenic CO_2 inventories in the ocean (Gruber *et al.*, 1996, Sabine *et al.*, 1999, Sabine *et al.*, 2002, Sabine *et al.*, 2004), ocean forward and inverse models (Sarmiento *et al.*, 2001; Gloor *et al.*, 2003), and combined use of atmospheric oxygen and CO_2 records (Keeling and Shertz, 1992, Keeling *et al.*, 1996). Given the significant uncertainties that are associated with each of these indirect methods, it is imperative to document the time evolution of surface ocean CO_2 concentrations over time.

The regional air-sea flux patterns are less well known, with significant disagreement among atmospheric inversions, ocean surface pCO_2 flux estimates and ocean numerical models (Takahashi *et al.*, 2002; Gurney *et al.*, 2002). The limited number of long-term ocean time series stations show significant biogeochemical variability from sub-diurnal to decadal timescales. Changes in large-scale ocean-atmosphere patterns such as El Niño/ Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) appear to drive much of the inter-annual variability, and this variability is expressed on regional (several hundred-to-thousands of kilometers) rather than basin-to-global scales. Large inter-annual variability in the partial pressure of surface water CO_2 (pCO_2) and CO_2 fluxes in the Equatorial Pacific are well documented (e.g. Feely *et al.*, 2002). The general magnitude and mechanisms of mid-latitude variability signals are less clear (LeQuere *et al.*, 2000; 2003), but significant year to year variability is evident in the subtropical Bermuda Atlantic Time-Series Station (BATS) and Hawaii Ocean Time-Series (HOT). Large annual and inter-annual variation in pCO_2 is also observed in sub-polar regions, but is very poorly characterized due to a lack of data.

The slower, decadal time-scale ocean responses (e.g., changes in nutrient stocks and community structure) are not as well characterized as the interannual response, though there is tantalizing evidence for large-scale biogeochemical regime shifts (or perhaps secular trends) (Karl, 1999) and changes in nutrient distributions (Emerson *et al.*, 2001). Distinguishing a human-induced, climate-change signal from natural decadal variability on this time-scale is often singularly difficult, particularly given the relatively short duration of most oceanographic data records. But model projections suggest that anthropogenic impacts are accelerating and may become more evident in the near future.

A wide variety of mechanisms have been identified that could conceivably alter ocean carbon uptake, but in many cases even the sign of the biogeochemical response, let alone the quantitative magnitude, is uncertain (Denman *et al.*, 1996; Doney and Sarmiento, 1999). Potential effects include:

- decreased calcification from lower pH and CO_3^{-2} ion concentrations resulting from anthropogenic

CO_2 uptake (Kleypas *et al.*, 1999; Riesebell *et al.*, 2000, Feely *et al.*, 2004);

- decreased vertical nutrient supply and in some regions enhanced, effective-surface-layer light supply leading to often opposing regional changes in primary productivity (Bopp *et al.*, 2001);
- alterations in the spatial patterns and community composition of marine biomes due to changes in stratification (Boyd and Doney, 2002);
- modifications in dust deposition and iron fertilization affecting the high nitrate-low chlorophyll (HNLC) regions such as the Southern Ocean and possibly subtropical nitrogen fixation;
- decoupling of carbon and macronutrient cycling because of shifts in the elemental stochiometry of surface export and differential subsurface remineralization.Accounting for such hypotheses in future climate projections is presently problematic given our current understanding and modeling tools (Doney, 1999; Falkowski *et al.*, 2000).

Time-series records are key to characterizing the natural variability and secular trends in the ocean carbon cycle and for determining the physical and biological mechanisms controlling the system. Year-to-year variations in physics (e.g., upwelling, winter mixing, lateral advection), bulk biological production, and ecological shifts (e.g., community structure) can drive significant changes in surface pCO_2 (and thus air-sea flux) and surface nutrient fields. The biological and chemical responses to natural perturbations (e.g., ENSO, dust deposition events) are particularly important with regard to evaluating potential climate responses and for evaluating the prognostic models used in future climate projections.

Ship-based time-series measurements are impractical for routinely measuring variability over intervals from a week to a month; they cannot be made during storms or high-sea conditions, and they are too expensive for remote locations. Instrumental advances over the past 15 years have led to autonomous moorings capable of sampling properties of chemical, biological, and physical interest with resolution as good as a minute and a duty cycle of a year or more (e.g., Chavez *et al.*, 1999; Dickey, 2003). This work has provided a growing body of evidence that episodic phenomena are extremely important causes of variability in CO_2 and related biogeochemical properties and processes. Time-series moorings are essential for documenting the temporal evolution of the ocean carbon system. These moorings, particularly when co-located with shipboard time-series programs, are also invaluable for developing and testing new chemical and biological techniques and autonomous sensors as well as serving as focal points for process studies.

The moored pCO_2 program started in 1996 as a collaborative research project between the Monterey Bay Aquarium Research Institute (MBARI) and NOAA's Pacific Marine Environmental Laboratory (PMEL). With support from the NOAA/OACES (then NOAA/OGP's Global Carbon Cycle program) and NASA/SIMBIOS programs, MBARI developed and deployed two pCO_2 systems on TAO buoys in the Equatorial Pacific (at 0°, 155°W and 2°S, 170°W). In 2002 NOAA's Global Carbon Cycle (GCC) program funded a proposal to begin transferring the pCO_2 system technology developed at MBARI to PMEL. In 2004, the moored CO_2 program was picked up by the Office of Climate Observations (OCO) as part of the ocean observing system for climate. The moored pCO_2 network is still in its infancy, but is quickly expanding into a global network of surface ocean and atmospheric CO_2 observations that will make a substantial contribution to the production of CO_2 flux maps for the global oceans. The long-term goal is to populate the network of OCEAN Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES; http://www.oceansites.org/OceanSITES/) so that CO_2 fluxes will become a standard part of the global flux mooring network. This effort has been endorsed by the OceanSITES science team. Additional information about the moored pCO_2 program can be found at: http://www.pmel.noaa.gov/co2/moorings/

1.2 Addressing NOAA's Program Plan

The moored pCO_2 program directly addresses key element 8) Ocean Carbon Monitoring Network, as outlined in the Program Plan, but also provides a value added component to elements 4) Tropical Moored Buoy Network and 6) Ocean Reference Stations. Within the Ocean Carbon Monitoring Network element, there are three major related components: repeat hydrographic sections, underway surface pCO_2 measurements, and moored pCO_2 measurements. Each component addresses a different timescale of variability. The moored pCO_2 program is designed to assess the short-term variability that cannot be accomplished with shipboard measurements. Obtaining long-term records of these high-resolution measurements allows a full integration of the short-term variability into the longer-term records obtained from the other elements of the CO_2 program. In particular, the moored pCO_2 data will directly contribute to the production of regional CO_2 flux maps and is being examined as a component of a new breed of data assimilation models that include estimates of carbon distributions and fluxes. The moored pCO_2 program is governed by the COSP Ten Climate Monitoring Principals.

1.3 National and International Linkages

Recognizing the need to develop an international framework for carbon research, various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the Intergovernmental Oceanographic Commission (IOC), and the Scientific Committee on Oceanic Research (SCOR) have worked together to develop research strategies for global carbon cycle studies. The two primary international ocean carbon research programs are the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere (SOLAS) programs. Both programs strongly recommend carbon time-series measurements. These programs are very supportive of NOAA's efforts to develop a global pCO_2 mooring network and a number of international colleagues have expressed interest in working with us to include carbon measurements on their moorings. Because ocean carbon is relevant to so many international programs, IOC and SCOR have co-sponsored the International Ocean Carbon Coordination Project (IOCCP). The goals of the project are to gather information about on-going and planned ocean carbon research and observation activities, to identify gaps and duplications in ocean carbon observations, to produce recommendations that optimize resources for international ocean carbon observations and the potential scientific benefits of a coordinated observation program, and to promote the integration of ocean carbon observations with appropriate atmospheric and/or terrestrial carbon activities. Since Christopher Sabine is the chair of this project, NOAA's moored pCO_2 program is well integrated into the international coordination efforts. In addition to providing direct links to the international research programs, our involvement in the IOCCP provides a link to the global observing programs such as GOOS, OOPC, GCOS, and JCOMM.

The primary large-scale ocean carbon program within the United States is the Ocean Carbon and Climate Change Program (OCCC). Carbon time-series measurements play a key role in the OCCC plan. The emphasis during the first part of OCCC Phase 1 is on maintaining existing open ocean Northern Hemisphere subtropical and equatorial stations and establishing new sites or augmenting ongoing time-series in the North Atlantic and North Pacific oceans as the groundwork for follow-on process studies. Pilot Southern Ocean time-series also need to be established a prelude to a major Southern Ocean process study in Phase 2. The NOAA moored pCO_2 network is a critical component for meeting these national plans and is being coordinated through Christopher Sabine who serves on the OCCC scientific steering committee.

FY 2005 PROGRESS

2.1 Background

Since December 1996, MBARI has collaborated with PMEL to maintain pCO_2 sensors that were developed by MBARI on two Tropical Atmosphere Ocean (TAO) moorings in the equatorial Pacific at 155°W, 0° and 170°W, 2°S. In 2002, the PMEL engineering and CO_2 groups started working with the MBARI group to take a similar MBARI designed pCO_2 system for a drifting buoy and modify it to work as a mooring based system. The major modifications from the original MBARI moored systems were the use of a different infrared detector (LiCor-820) that would allow direct measurements of surface ocean and atmospheric CO_2 concentrations rather than just the air-sea CO_2 difference and the addition of a NOAA/CMDL certified standard gas that would allow the system to recalibrate autonomously and be tied directly to the World Meteorological Organization atmospheric CO_2 standards. The new pCO_2 systems were designed to allow any single component of the system to be easily exchanged, even on a deployed buoy if necessary. These new systems, which are built and maintained by PMEL, were deployed in September 2003 at 125°W, 0° and 140°W, 0° to augment the two original MBARI systems. In 2004, this project was officially transferred to the Office of Climate Observations (OCO) to be expanded into a global moored pCO_2 network. At that time an additional PMEL pCO_2 system was built and placed on the new MOSEAN mooring deployed north of Honolulu at the Hawaii Ocean Time-series site (158°W, 22°N). This brought the total mooring project to a total of 5 sites.

2.2 Measurements and Network Development

The moored pCO2 systems collect CO_2 and O_2 data from surface seawater and marine boundary air every three hours. A summary file each of the measurements is transmitted once per day and plots of the data are posted to the web. In addition to the moored pCO2 data collected as part of this project, MBARI has been collecting nutrient and chlorophyll measurements on the 125°W, 140°W, 155°W, 170°W TAO cruises. One person participates on these cruises and analyzes samples from the shipboard uncontaminated seawater supply and from CTD casts performed in-between buoy maintenance. These data have proven to be very helpful at interpreting the buoy based measurements and ultimately trying to examine the mechanisms controlling the observed variability in pCO_2.

In FY05, PMEL/MBARI maintained the 5 sites from FY04 and PMEL also instrumented 3 new sites. New pCO_2 systems were placed on a TAO buoy at 170°W, 0°, on the Kuroshio Extension Observatory (KEO) buoy at 144.5°E, 32.3°N, and on the Bermuda Testbed Mooring (BTM) at 64°W, 31°N (Figure 1). One new pCO_2 system was also built to replace a mooring that was lost at sea earlier in the year. The number of total deployments increased from 4 in FY04 to 9 in FY05. To support these new and existing sites, 5 TAO buoy hulls were modified to support pCO_2 systems. One of these modified hulls was to replace the mooring that was lost at sea.

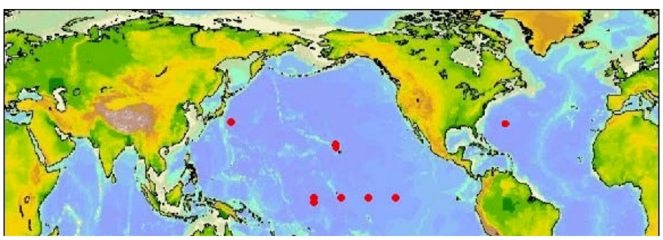

Figure 1. Map of moored pCO_2 systems currently deployed at part of this program.

The original MBARI-built pCO_2 systems directly measured the air-sea pCO_2 difference. In June/July 2005 the two MBARI moorings were upgraded to LiCor-820 systems that measure the air and water pCO_2 independently and are more compatible with the measurements made by the PMEL systems at other locations. These systems were also scheduled to sample every hour instead of every 3 hours to ensure that we are not missing important short time-scales of variability with the standard 3 hour sampling mode.

2.3 Instrument/Platform Acquisitions

Here we summarize the deployment schedules and instrument performance over the last year. Systems are grouped into three categories. Five systems are located in the equatorial Pacific on the TAO moorings. Two systems are located in the North Pacific and North Atlantic subtropical gyres on Woods Hole buoys. These systems are co-located with the Hawaii and Bermuda shipboard time-series study sites. One system is located off of Japan in a modified TAO buoy operated by Meghan Cronin (PMEL) as part of an OCO funded OceanSITES flux mooring.

2.3.1 Equatorial Pacific on TAO Moorings:

125°W, 0° - This PMEL-built system was functioning properly from May 2004 until the entire mooring was lost due to vandalism on December 20, 2005. Another system was redeployed on March 16, 2005 and worked well until September 15, 2005 when the system stopped sampling the surface seawater CO_2. We continue to get good atmospheric CO_2 measurements, but it is believed that a valve failure has caused the water measurements to not function properly. This system is scheduled to be replaced in January or February 2006. The percent data return (only counting times when all data streams are good) is as follows: FY04, 40%, FY05 72% and Lifetime 56%.

140°W, 0° - This PMEL-built system was recovered and redeployed in March and again in September 2005. This system is scheduled to be replaced in January or February 2006. The percent data return is as follows: FY04, 36%, FY05 98% and Lifetime 67%.

155°W, 0° - This MBARI-built system was recovered and redeployed in November 2004 and again in June 2005. In June the system was upgraded to the LiCor-820 system, however during deployment we believe the battery may have been damaged. The system failed a few weeks after deployment. The system is scheduled to be repaired or replaced as necessary in early November. The percent data return is as follows: FY04, 41%, FY05 64% and Lifetime 52%.

170°W, 2°S - This MBARI-built system was not operating properly the first half of the year. It was recovered and replaced in July 2005 with a LiCor-820 system. It has been functioning properly since the July 1st deployment. The percent data return is as follows: FY04, 3%, FY05 25% and Lifetime 14%.

170°W, 0° - New Deployment Location. This PMEL-built system was first deployed on July 4, 2005. It is working properly. The percent data return is as follows: FY05 100% and Lifetime 100%.

2.3.2 HOT/BATS on WHOI designed buoys

MOSEAN buoy at Hawaii Ocean Time-series site (158°W, 22°N) - At the beginning of FY05, the PMEL-built system on this mooring was malfunctioning due to fact that the mooring had flipped for 3 hours during the deployment. While upside down, the air intake drew water into the system. On December 19, 2005, a new system was deployed and the data has been good since that time. The mooring was recovered and redeployed in May 2005. The percent data return is as follows: FY04, 0%, FY05 84% and Lifetime 73%.

Bermuda Testbed Mooring (64.2°W, 31.7°N) - New Deployment Site. This mooring was scheduled to be deployed at the end of September 2005. Due to unfavorable weather conditions the deployment did not occur until October 22, 2005. The PMEL-built system is operating properly.

2.3.3 OceanSITES Flux Moorings

Kuroshio Extension Observatory (144.5°E, 32.3°N) - New Deployment Site. The mooring at this location was redeployed with a PMEL-built moored pCO_2 system on board in May 2005. A few days after deployment, it became obvious that the equilibrator portion of the system was malfunctioning while the air measurements were operating properly. The cause of the problem is believed to be a valve that was meant to vent the equilibrator, but it will not be possible to know until the system is recovered. The other parts of the system functioned properly until September 12, 2005 when some electrical problems, perhaps associated with the original failure, resulted in a complete system failure. This system is scheduled to be replaced in May 2006.

2.4 Data Processing

All the PMEL summary files are processed and graphed on a website that is updated daily <http://www.pmel.noaa.gov/co2/moorings/>. The data are currently stored at PMEL and are available from Christopher Sabine at PMEL. The MBARI data are available from Francisco Chavez at MBARI. The carbon data management and synthesis teams are in the process of integrating the moored pCO_2 data together with the underway pCO_2 data that are being collected through a related OCO project. Ultimately all of the surface CO_2 data will feed into the seasonal CO_2 flux map effort that is currently under development.

All systems are thoroughly tested and calibrated over a wide range of CO_2 concentrations using WMO traceable standard gases in the laboratory before deployment. The systems are then calibrated with a zero and WMO traceable span gas at the beginning of every three hour measurement cycle during the deployment. We have been working this year to develop a system for processing the moored pCO_2 data that is collected. This involves the development of automated quality control procedures and post deployment calibration efforts. To finalize a dataset, the data are compared to any underway pCO_2 data that are available as well as the Marine Boundary Layer (MBL) atmospheric CO_2 concentrations for a given buoy location as provided by NOAA's GLOBALVIEW-CO_2 network. Based on these comparisons and various diagnostics of the automated system calibration information, the entire data set (air and water values) may be adjusted to match these higher accuracy measurements. Typically these adjustments are less than a couple of parts per million. The data are then merged with sea-surface temperature and salinity data collected by other groups on the same buoy. We have also developed automated routines for examining data spikes. Based on the calibration, atmosphere, and seawater information as well as other diagnostic measurements for each identified point relative to the surrounding points, the data point may be flagged as questionable or bad. Typically less than 2% of the data are flagged as questionable or bad. As all data become available, final calibrated data are archived at the Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic Data Center (NODC) on a yearly basis. As of this report, all PMEL data through September 2004 have been finalized and submitted to CDIAC for public release. We anticipate being able to maintain or improve upon the one year final data release for the foreseeable future.

2.5 Logistical Considerations and Improvements

The pCO_2 systems are mounted in buoys that are deployed from a ship. Currently all of our deployments are in conjunction with another project that is covering the buoy deployment and maintenance costs and has already allocated ship time. The pCO_2 systems are typically sent out on a cruise and are set up and deployed by a member of the scientific party as an ancillary task. This arrangement requires about 4 hours for setup and then approximately 10 additional man hours during the cruise. During the past year we have developed a floating equilibrator that has eliminated the need for a buoy visit with a small boat to adjust the equilibrator depth. This improvement in the system has greatly simplified the logistics of deployment.

The pCO_2 systems we are using are designed to be add-

on instruments to existing moorings. These systems typically do not measure all of the parameters needed to determine the air-sea flux of CO_2. Therefore, we rely on measurements of sea surface temperature, salinity and winds from other systems on the buoys. As the network expands, however, the needed ancillary measurements may not always be available. Our group has been working to add additional capabilities to the systems to make them more self-sufficient, allowing more flexibility with the types of platforms on which they can be deployed. These capabilities include the addition of sensors for sea surface salinity, sea surface temp, wind, digital compass, and GPS. These additional sensors will only be deployed where a mooring does not already have these sensors.
Another improvement was to make the transmission apparatus more robust by enclosing the antenna and modem together into a protective can. Moving the modem close to the antenna allowed the cable to the transmitter to be upgraded from an RG8 cable to a much more robust serial cable. The antenna can also has a GPS receiver that was added to the system to provide real-time locations for tracking the buoy if it were to break free from its mooring. Many other improvements were made to the software to make the system easier to use for the personnel who were deploying systems as ancillary tasks.

The nutrient and chlorophyll measurements require a person to be aboard each cruise to process samples. Where possible, this person also takes responsibility for the pCO_2 system deployments.

2.6 Analysis and Research Highlights

The time series of ΔpCO_2 collected by MBARI in the equatorial Pacific and the coast of California now represent the longest records of their kind anywhere in the ocean. The California efforts have been funded primarily through the David and Lucile Packard Foundation and developmental efforts continue in this location. The equatorial Pacific systems (Figure 2) are now part of the growing global moored pCO_2 network funded by NOAA's Office of Climate Observations. These data have been used to help quantify the magnitude of the seasonal and interannual variability in this region. They have also been used to document the significant changes in CO_2 flux associated with El Niño (e.g. Chavez *et al.*, 1999).

In recent years the moored CO_2 network has grown substantially from the initial two equatorial sites. CO_2 moorings are now located along the equator at 125°W, 140°W, 155°W, and 170°W (Figure 3). The data records

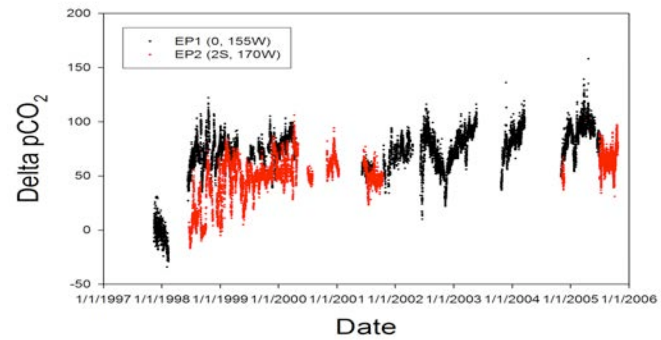

Figure 2. Time series of ΔpCO_2 at moorings EP1 (0°, 155°W-black) and EP2 (2°S, 170°W-red) from late 1997 to the present.

at some of these sites are not very long, but already it is clear that all of the sites show variability over a variety of time scales from diurnal to seasonal and interannual. Some of these patterns are coherent at all of the locations and others are not. In an attempt to begin to understand the mechanisms driving these modes of variability, we have begun examining some of these sites more closely.

For example, a plot of surface seawater pCO_2 versus sea surface temperature (SST) at the 125°W, 0° mooring during 2005 shows three distinct trends in the data (Figure 4). One trend (indicated with the red line) falls right along the large-scale equatorial Pacific CO_2 versus SST relationship as described by Cosca *et al.* (2005). This relationship is controlled by the upwelling of cold, high CO_2 water along the equator. There is another grouping of data, however, that shows an equally large temperature range, but with almost no corresponding change in CO_2. Preliminary analysis indicates that this temperature variability is driven by the passage of Kelvin Waves past the mooring site. These Kelvin Waves tend to move water in an east-west direction.

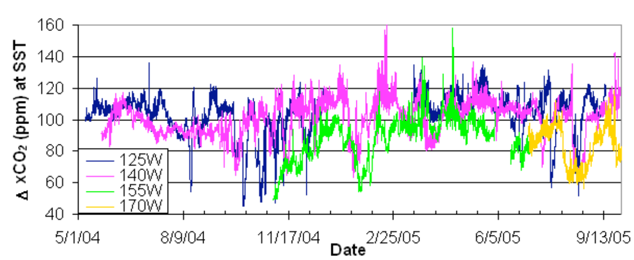

Figure 3. Plot of the sea-air difference in CO_2 mole fraction on the Equator at 125°W, 140°W, 155°W, and 170°W. Some variations are coherent across longitudes while others are not.

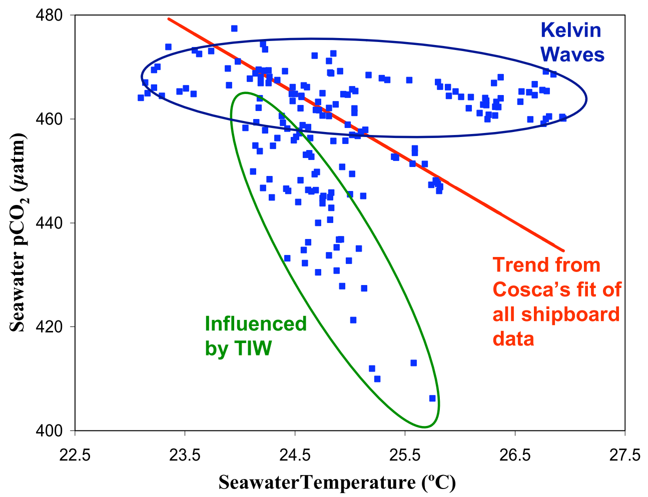

Figure 4. Plot of the partial pressure of CO_2 (pCO_2) in surface seawater versus sea surface temperature for 2005 data from the 125°W, 0° mooring. Lines and circles indicate three distinct influences on the CO_2 trends.

Since there are strong zonal gradients in sea surface temperature along the Equator this movement generates variability in the SST at the mooring site. There is little variability in the zonal pCO_2 gradients in this region because the thermodynamic drive to increase CO_2 as the water warms is nearly exactly counteracted by the loss of CO_2 to the atmosphere. Consequently, the Kelvin Wave generates a relatively large temperature anomaly with a relatively minor CO_2 anomaly. On the other hand, the passage of tropical instability waves tends to move water in a north-south direction. The meridonal gradients in pCO_2 are much larger for a given temperature range than the zonal gradients, therefore a third trend can be seen in the data with a relatively large pCO_2 change for a rather modest temperature change. This third trend represents the effect of the passage of tropical instability waves.

While this work is still preliminary, it does suggest some interesting mechanisms responsible for the observed variability at this site. We are continuing to examine the mechanisms at this and other equatorial sites and hope to submit a manuscript for publication in FY06. A better understanding of these mechanisms will lead to improved carbon models and more accurate predictions of the oceanic sources and sinks for CO_2 in the future.

The co-location of two moored pCO_2 systems with ship-board time-series sites in the North Pacific and North Atlantic subtropical gyres is also starting to provide some interesting insight into the mechanisms controlling CO_2 variability in these regions. For example, using satellite derived ocean color a ~200 km in diameter, spatially coherent region of enhanced chlorophyll concentrations was observed in the immediate vicinity of Station ALOHA around the last week of July 2005. Based on analyses of satellite derived sea surface altimetry and surface currents, the feature appeared associated with an anti-cyclonic eddy traveling to the south-west into the vicinity of Station ALOHA and the MOSEAN mooring. At the same time, a 15 ppm drop in surface water pCO_2 that was not consistent with the overall seasonal trend was observed in the near-real time transmissions from the MOSEAN CO_2 system (Figure 5). To assess the influence of such events on upper ocean biogeochemistry the HOT personnel conducted a spatial transect from the approximate center of the region of enhanced chlorophyll toward the western edge of the chlorophyll feature. Based on microscopic analyses, the bloom appeared to be primarily supported by large diatoms but also showed increased abundances of nitrogen-fixing bacteria. Similar diatom-diazotroph blooms appear to be a regular occurrence during the summertime months throughout the subtropical North Pacific. The wide range of satellite, ship-board, and mooring data collected from this event will allow a comprehensive evaluation of this feature and may shed light on the significance of these events to the ecosystem balance of the North Pacific and the ocean carbon cycle. An abstract has been submitted to present these early results at the Ocean Sciences meeting in February 2006.

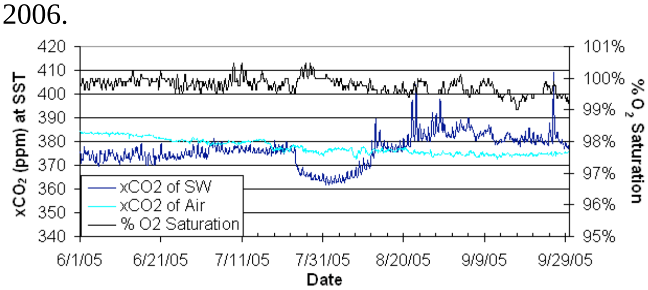

Figure 5. Plot of atmospheric and surface ocean CO_2 mole fraction along with the percent oxygen saturation in surface waters around the time of that a phytoplankton bloom was observed from ocean color satellites. Note the bloom induced drop in xCO_2 on 7/24-8/15.

4. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO_2 Measurements

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PROJECT SUMMARY

The *Second Report on the Adequacy of the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC)* concludes, in agreement with the Intergovernmental Panel on Climate Change (IPCC), that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. One aspect of the effort to redress the identified deficiency has been to expand the surface ocean pCO_2 measurement program in the hopes of quantifying our understanding of the seasonal and interannual variability of air-sea CO_2 fluxes in the world oceans. While there is a reasonably good understanding of the major sources and sinks of CO_2 based on the sea surface pCO_2 climatology developed by Takahashi et al. (2002), the motivation for this study is to produce the optimal global pCO_2 sampling network design by updating, expanding and extending the preliminary effort of Sweeney et al. (2002) who made a region-by-region estimate of the sampling required to quantify fluxes of CO_2 to the nearest 0.1 Pg C/year (See Fig. 1).

Specific questions to be addressed include:

- What is the effect of seasonality on variability in surface pCO_2?
- Which sampling locations will be most representative of large-scale seasonal, interannual and decadal changes in the surface ocean pCO_2 and air-sea CO_2 flux?

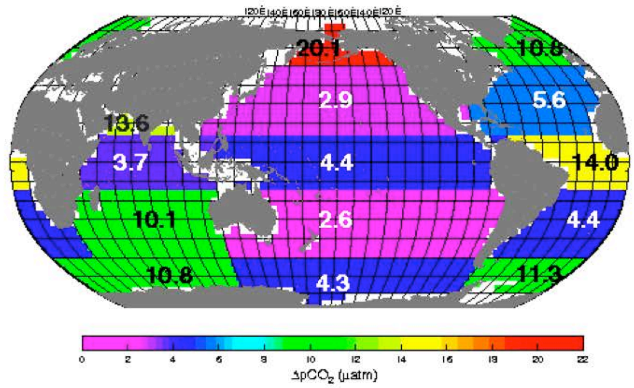

Fig 1. – Target DpCO2 to estimate a regional CO2 flux within ± 0.1Pg-C/yr for the major oceanic regions.

- Which sampling locations will lead to the early detection of changes in surface pCO_2 concentrations and associated fluxes due to climate change?

The Sweeney et al. (2002) study suggests that a desired uncertainty of ±0.1 Pg C/yr in the basin-scale mean annual estimates for net sea-air CO_2 flux may be achieved by evenly time-spaced measurements of pCO_2 **6–15 times a year** throughout the regions of the world ocean with evenly spaced sampling **200–1500 km apart** (or 2–20 degrees longitude, depending on region and latitude). This study will recalculate these targets using both a global pCO_2 database compiled from measurements made by the international carbon community (See Figs. 2, 3, 4), as well as output from simulations of future climate produced by GFDL's Earth System Model (See Fig. 5). As an integral part of this study we examine both high-resolution measurements made throughout the World Ocean and the NOAA/GFDL Earth System Model to identify the optimal observation network design to capture variability in surface water pCO_2 and the resulting air-sea flux from the seasonal to decadal time frames. The use of hind-cast and forecasting biogeochemical simulations produced in support of the most recent IPCC Scientific Assessment (AR4) will allow us to identify key locations where we expect to observe natural and anthropogenic trends.

Addressing NOAA's Program Plan

Optimal design of the pCO_2 sampling network design using both the global database of pCO_2 measurements and simulations of future climate from GFDL's Earth System Model will help NOAA cost-effectively develop the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system. The goal of this data and model-based pCO_2 sampling network design is to quantitatively assess the optimum sampling strategy based on the long-term observational requirements of the operational forecast centers, international research programs and major scientific assessments.

International Linkages

Research strategies for global carbon cycle studies have been developed by various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Program (IHDP), and the Intergovernmental Oceanographic Commission (IOC) working together. To achieve the goal of a global carbon synthesis, there is an immediate need for global-scale coordination of international carbon observation and research efforts. This study fulfills one component of the urgent need to critically assess the overall network of planned observations to ensure that the results, when combined, will meet the requirements of the research community. By providing an optimal network design for a global pCO_2 measurement program, we will have the potential to contribute to the International Ocean Carbon Coordination Project (IOCCP). We will also contribute to regional efforts such as CARBOOCEAN in the Atlantic and the PICES Working Group 13 in the North Pacific that are coordinating observations.

FY 2005 PROGRESS

Of the three integrated components of the optimal network design, we have

1.) **Completed** global pCO_2 database assembly for analysis - over 1.8 million measurements (See Figs. 2, 3).
2.) **Begun** analysis of seasonality, length and time scale of pCO_2 variability within the global pCO_2 database (See Fig. 4).
3.) **Begun** analysis of seasonality, length and time scale of pCO_2 variability with the GFDL Earth System Model (See Fig. 5).

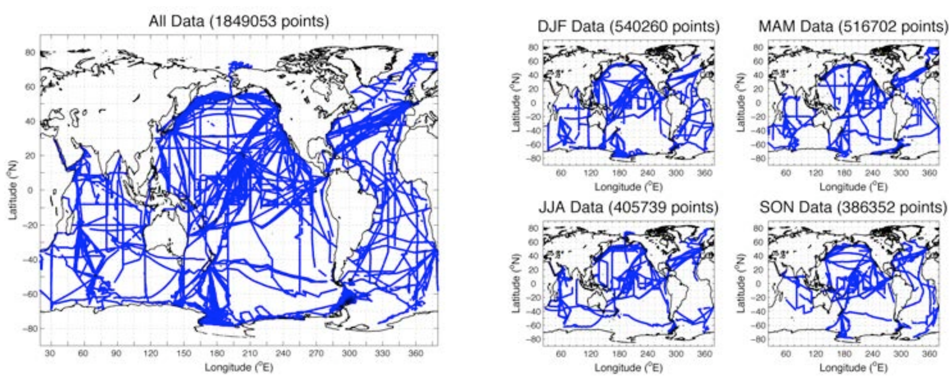

Fig. 2a – Spatial distribution of pCO_2 measurements in the global pCO_2 database. Fig. 2b - Seasonal distribution of pCO_2 measurements in the global pCO_2 database compiled for this study (DJF is Dec-Feb, MAM is Mar-May, JJA is Jun-Aug, SON is Sep-Nov).

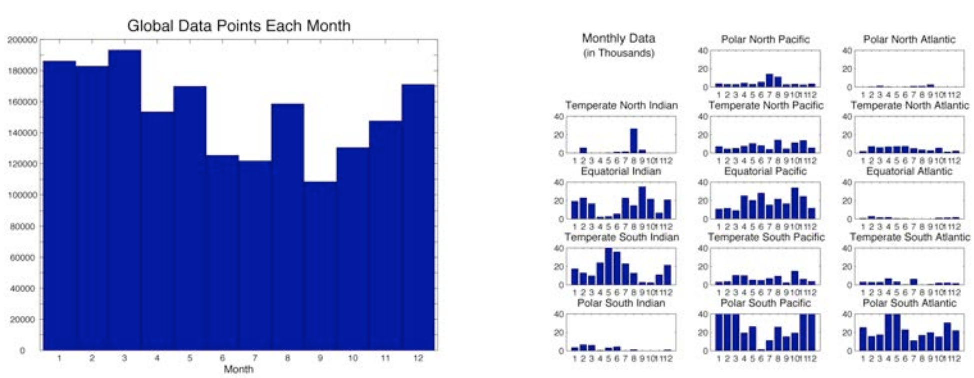

Fig. 3a – Temporal distribution of pCO_2 measurements in the global pCO_2 database (Jan = month 1). Fig. 3b – Temporal distribution of pCO_2 measurements within regions in the global pCO_2 database compiled for this study.

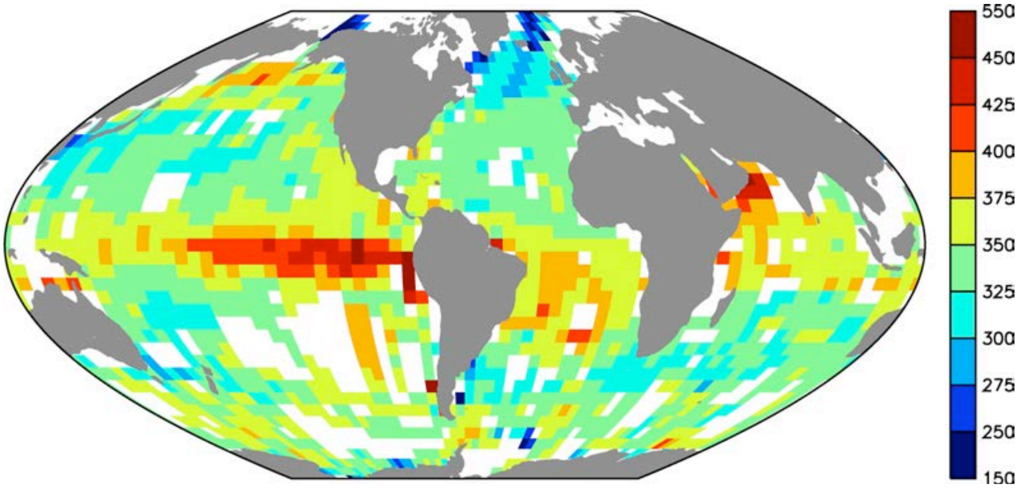

Fig. 4a – Annual average of monthly mean value of fCO_2 (ppm) in 4°x5° bins from global database of pCO_2 measurements.

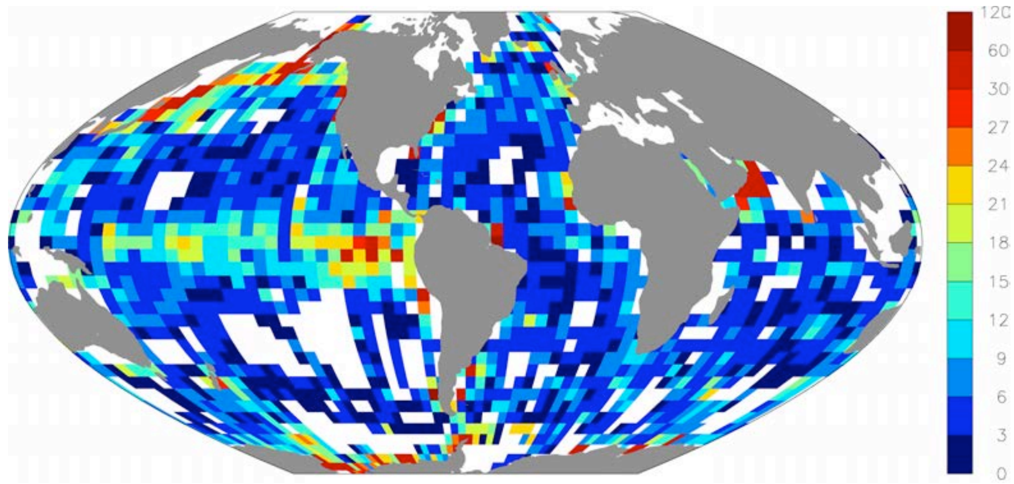

Fig. 4b - Annual average of monthly fCO_2 (ppm) standard deviation in 4°x5° bins from global database.

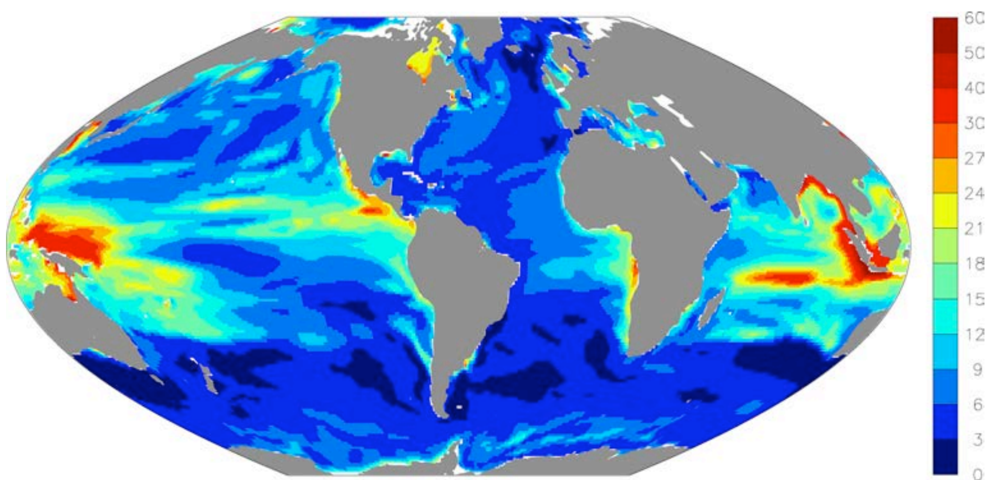

Fig. 5 –Annual average of monthly standard deviation of dissolved inorganic carbon in the GFDL Earth System Model (mmol/kg)(0-100m).

Arctic Ocean Observing System

1. United States Interagency Arctic Buoy Program

Magda Hanna[1], Ignatius G. Rigor[2], Participants of the International Arctic Buoy Programme[3]
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PROJECT SUMMARY

A network of automatic data buoys to monitor synoptic-scale fields of sea level pressure, surface air temperature, and ice motion throughout the Arctic Ocean was recommended by the U.S. National Academy of Sciences in 1974. Based on the Academy's recommendation, the Arctic Ocean Buoy Program was established by the Polar Science Center (PSC), Applied Physics Laboratory, University of Washington, in 1978 to support the Global Weather Experiment. Operations began in early 1979, and the program continued through 1990 under funding from various agencies. In 1991, the International Arctic Buoy Programme (IABP) succeeded the Arctic Ocean Buoy Program, but the basic objective remains – to maintain a network of drifting buoys on the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements (Figs. 1 & 2) and research purposes including support to the World Climate Research Programme and the World Weather Watch Programme.

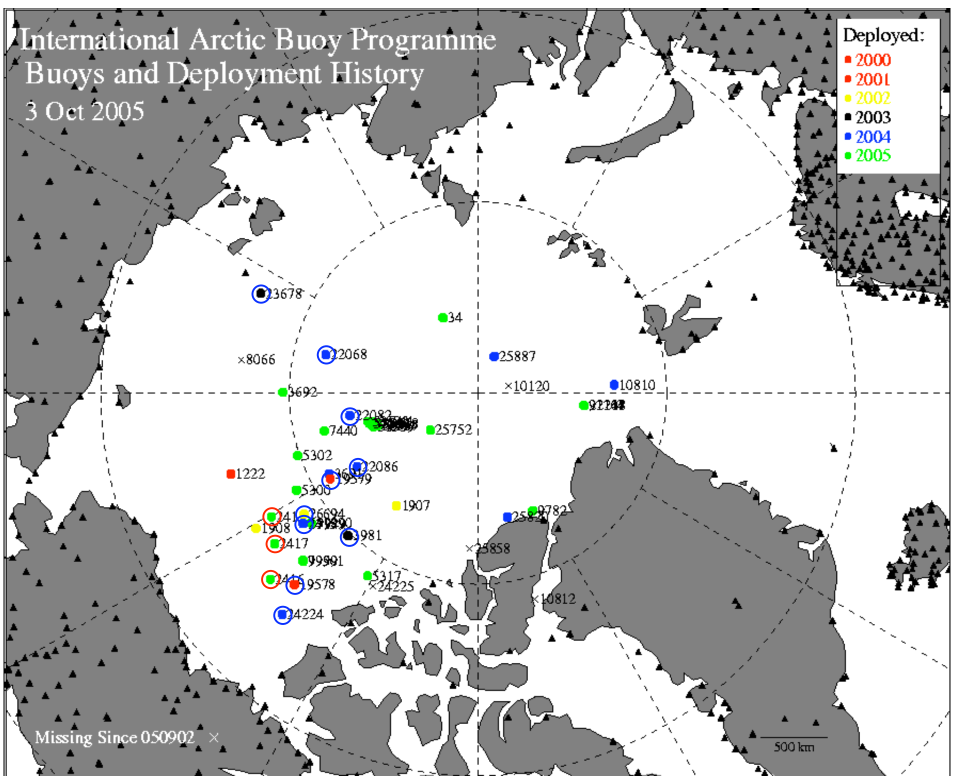


Figure 1. This map shows the IABP drifting buoys reporting on 3 October 2005 color coded by the year that the buoys were deployed. During this past year, 26 buoys were deployed (green dots), maintaining an array of 48 drifting buoys. The buoys circled in red were purchased using funds provided by the NOAA Office of Climate Observation in 2005. The Argos data processing costs for the fourteen buoys circled in blue and red are covered by this funding.

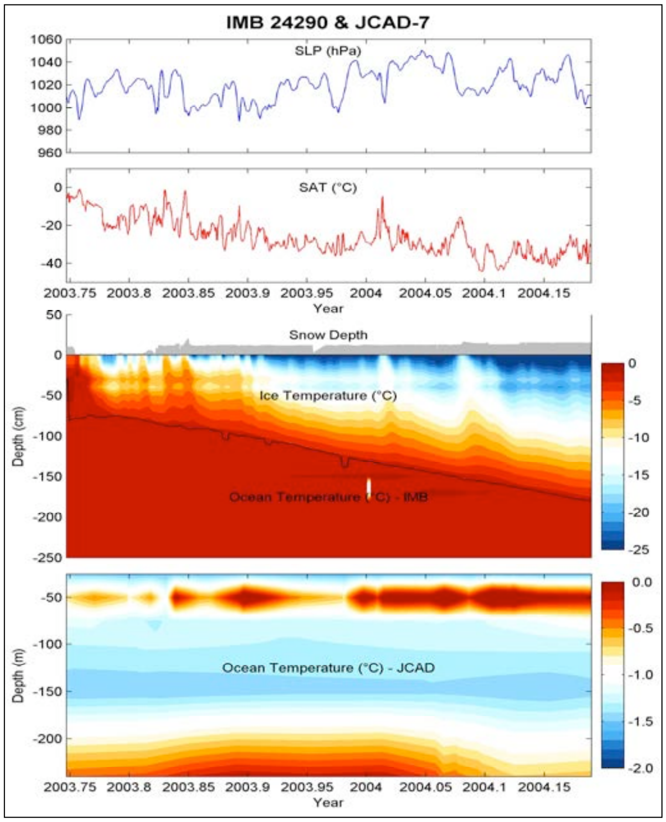


Figure 2. Observations from Ice Mass Balance (IMB) buoy 24290 and JAMSTEC Compact Arctic Drifter (JCAD) 7, which were deployed together on the drifting Arctic sea ice. These buoys measure sea level pressure (SLP), surface air temperature (SAT), ice thickness and temperatures, snow depth, and ocean temperatures and salinity. From these measurements, we can also estimate a number of other geophysical quantities such as ocean surface heat flux and heat storage.

History

The IABP evolved from a succession of buoy programs beginning with the Arctic Ocean Buoy Program of the PSC. These programs were initially funded by grants for basic research, but interest and support increased as the community recognized the operational value of the data.

In 1990, the National Ice Center (NIC) was designated as the focal operational organization for U.S. buoys on the Arctic Ocean, with responsibility for the overall management and cooperation. The United States contribution to the IABP is coordinated through the United States Interagency Arctic Buoy Program (USIABP), which is managed by the National Ice Center (NIC) and the PSC. The USIABP is a collaborative program that draws operating funds and services from a number of U.S. government organizations and research programs. These organizations include the International Arctic Research Center at the University of Alaska Fairbanks, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, the Naval Oceanographic Office, the NIC, the Office of Naval Research, and the U.S. Coast Guard. From these contributions the USIABP acquires and deploys buoys on the Arctic Ocean, and supports the Coordination and Data Management for the IABP by the PSC.

Today, the IABP is composed of 20 different research and operational institutions from 9 different countries. The IABP is funded and managed by Participants of the program. Management of the IABP is the responsibility of the Executive Committee, and operation of the program was delegated to the Coordinator of the IABP, Ignatius Rigor. The primary contribution of the USIABP to the IABP is to support the coordination and data management of the IABP.

Scientific Rationale

Dramatic changes in Arctic climate have been noted during the past two decades. It should be noted that many of these changes were first observed and studied using data from the IABP, which is analyzed and made available to the community by the PSC. For example, IABP data were fundamental to Walsh et al. (1996) showing that atmospheric pressure has decreased, Rigor et al. (2000) showing that air temperatures have increased, and to Proshutinsky and Johnson (1997); Steele and Boyd, (1998); Kwok, (2000); and Rigor et al. (2002) showing that the clockwise circulation of sea ice and the ocean has weakened. Data from the IABP has also been assimilated into the global temperature data sets (e.g. Jones et al., 1999). All of these results relied heavily on IABP data. And, as such, maintaining and enhancing the IABP has been identified as a priority for the Study of Environmental Arctic Change (SEARCH).

In addition to supporting these studies of climate change, the IABP observations are also essential for:

1. ***Forcing, assimilation and validation of global weather and climate models.*** The buoy data has been used to validate the Polar Ice Prediction System model developed at the Naval Research Laboratory, and are assimilated into the National Center for Environmental Prediction – National Center for Atmospheric Research reanalysis data sets (Kalnay et al. 1996), Fleet Numerical Meteorol-

ogy and Oceanography Center (FNMOC) and the Naval Oceanographic Office (NAVO).

2. ***Validation of satellite retrievals of environmental variables.*** The buoy data are used to validate satellite estimates of sea ice motion (e.g. Lindsay and Stern, 2003), and surface temperatures (e.g. Comiso, 2003).
3. ***Forecasting weather.*** For example, in Fig. 3, we show a storm off the coast of Alaska whose strength and trajectory would have been difficult to predict without observations from the buoys.

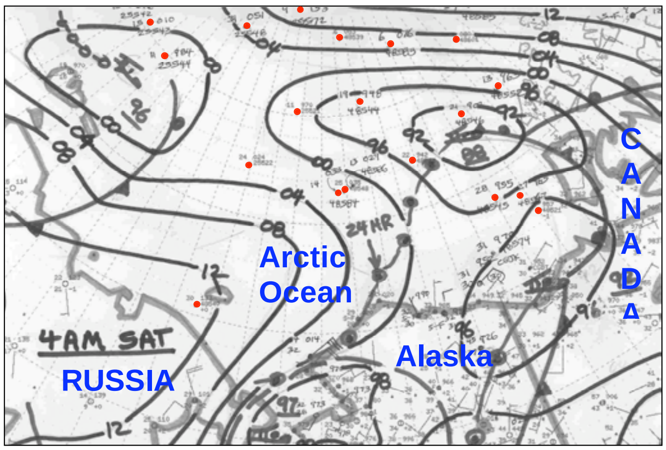


Figure 3. The observations (red dots) from the IABP are essential for analyzing and forecasting weather and sea ice conditions in the Arctic. In this example, we show how observations from the IABP are essential in detecting and estimating the strength of storms approaching Alaska from the Arctic Ocean. (Courtesy of Eric Stevens, NWS)

4. ***Predicting sea ice conditions.*** Our ability to accurately forecast sea ice conditions depends on observations of surface air temperature and sea ice motion over the Arctic Ocean. For example, during the summers of 2002 and 2003, colder than normal air temperatures were observed over the Alaskan coast (e.g. Serreze et al. 2003), and yet record minima in sea ice extent were observed. In order to explain this paradox, Rigor and Wallace (2004) hypothesized that these recent minima may be due to changes in the thickness of sea ice blown towards the Alaskan coast by the surface winds. To show this, they used a simple model to estimate the age of sea ice based on the observed drift (residence time) of the sea ice provided by the buoys. They showed that the age (and thickness) of sea ice has decreased dramatically in the 1990's, and this younger, thinner sea ice was observed to drift towards the Alaskan coast during the last few years. They argued that although temperatures may have been colder, the air was still warmer than the melting temperature of sea ice, and it simply takes less heat to melt younger, thinner sea ice, thus explaining the recent record minimums in sea ice extent during the last four summers.

Over 500 papers have been written using data from the IABP (A growing list of these citations can be found at http://iabp.apl.washington.edu/Citations.). Needless to say, the observations and datasets of the IABP data are cornerstones for environmental forecasting and research in the Arctic.

USIABP: Addressing NOAA's Program Plan

The USIABP embodies the following goals described by *Building a Sustained Ocean Observing System for Climate*:

1) The USIABP leverages international partnerships for its success. While the USIABP compiles primarily U.S. funding, the program functions in collaboration with eight other countries to form the International Arctic Buoy Programme. These partnerships aid the logistics of deploying buoys as well as ensure continuity in maintaining a sustainable set of Arctic observations.
2) The USIABP supports both ocean and atmospheric components. Data are collected by both the ICEX air buoy which measures basic atmospheric parameters as well as the Ice Mass Balance (IMB) buoy which measures oceanographic parameters (see Fig. 2).
3) The USIABP has effectively delivered continuous, long term, climate quality, global datasets for over 25 years. These data are archived and used for research, contributing to over 500 publications (available at http://iabp.apl.washington.edu/).

USIABP as a component of JCOMM

The USIABP falls under the Joint WMO/IOC Commission for Oceanography and Marine Meteorology (JCOMM) Observations Programme Area as a component of the Data Buoy Cooperation Panel (DBCP). A DBCP representative attends all meetings of the IABP.

USIABP managed in accordance with the Ten Climate Monitoring Principles.

For example, the IABP has been monitoring the remote, data sparse Arctic Ocean since 1979 and provides the longest continuing observational data set for the region. Our data analysis procedures and methods are documented in peer reviewed publication, annual data reports, and through our web pages. The data from this program is provided to the operational community through the GTS, quality controlled and analyzed for research by the PSC, and archived at the WDC-A.

FY 2005 PROGRESS

Maintaining the IABP Buoy Network

Using funds from this grant in 2005, we purchased three ICEXAIR buoys which were deployed by the Naval Oceanographic Office this past September (red dots on Fig. 1). Those three ICEXAIR were three of a total 19 buoys deployed using the logistics of the USIABP. USIABP deployment logistics include the seven ICEX Air buoys deployed by the Naval Oceanographic Office-sponsored White Trident Mission and the twelve buoys deployed by the USCGC Healy while deployed in the Arctic. Those buoys were three of a total of seven buoys directly purchased using funds of USIABP and three of a total of 26 buoys deployed by the international organization, IABP in 2005. The three buoys are all currently reporting in the array and we thus have a 100% success rate for FY2005 buoys purchased with this grant.

In FY2004, the USIABP was able to directly purchase four buoys and USIABP logistics deployed seven buoys total. The four buoys were part of the total of 28 buoys deployed by IABP in 2004. Of those four buoys purchased by USIABP, three are currently reporting. No funds were received by this grant to cover buoy hardware in FY2004.

This grant also provides Argos data processing for the fourteen currently reporting buoys (from FY02-FY05) owned by the USIABP (blue and red circled dots on Fig. 1). For operational use, these data are available in near real-time through the Global Telecommunications System. For research, the data from the Ice Mass Balance buoys are included in the data bases of the IABP which are analyzed at the PSC, and are available through the IABP web server (http://iabp.apl.washington.edu/). The data are also archived at the World Data Center for Glaciology.

1. A Web Site for the Global Ocean Data Assimilation System: A Linkage Between Model and Observations

Yan Xue
NOAA/NWS/NCEP/Climate Prediction Center, Camps Springs, MD

PROJECT SUMMARY

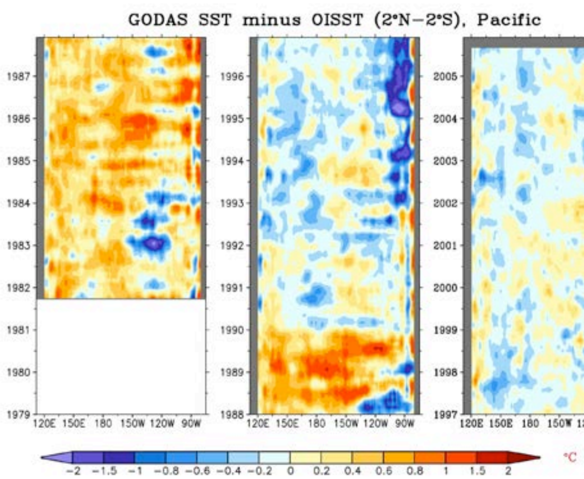
The objective of this project is to build a web site for the Global Ocean Data Assimilation System (GODAS) of the National Environmental Prediction Center (NCEP). The project is aimed at filling the gap in delivery of ocean analyses as an end product of ocean observations, as discussed at the 2005 Annual System Review of the Office of Climate Observation (OCO). The GODAS ocean analysis for 1979-present will made available to the public through the Environmental Modeling Center of NCEP, which is the producer of the GODAS data set, while the application of the GODAS data set in operational climate forecast is largely the responsibility of the Climate Prediction Center (CPC) of NCEP. This project extends CPC's responsibility to the area where it serves as a communicator between GODAS producers and users. This project is expected to grow in the direction where the needs of the user community go.

Background:

One of the main objectives of the in situ network managed by the NOAA's Office of Climate Observation (OCO) is to provide ocean observations to increase our understanding of the dynamics of the seasonal to interannual (SI) variability, and to improve the forecast skill of the SI variability. This has been largely done through a delivery of ocean analysis as an end product of ocean observations. Since 1995, the National Environmental Prediction Center (NCEP) has been producing ocean analysis for the Pacific Ocean by assimilating observations into an ocean model forced by atmospheric fluxes. The assimilated observations include temperature profiles from XBT, profiling floats and TAO moorings. The Pacific Ocean analysis (referred as RA6 hereafter) has been used to initialize the oceanic component of the NCEP's coupled atmosphere-ocean general circulation model, and has been shown to improve the forecast skill of SI variability significantly (Ji et al. 1998). In 2003, a Global Ocean Data Assimilation System (GODAS) was developed that uses the Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model version 3 forced with the atmospheric fluxes from the NCEP's Reanalysis 2, and assimilates not only temperature but also synthetic salinity constructed with a local temperature-salinity climatology. A retrospective global ocean reanalysis for 1979-2004 has been generated. The GODAS produces both pentad and monthly oceanic fields in real time, and is a unique dataset to serve research, application, and operational communities.

The quality of the GODAS ocean analysis has been evaluated against various independent data sets such as ocean currents from TAO moorings and drifter velocity program, CTD and ADCP data from cruises, tide gauges and altimetry sea level. It is found that the temperature field in GODAS is closer to observations than that in RA6. Although this version of GODAS does not assimilate satellite sea level as RA6 does, GODAS does as well as or better than RA6 in comparisons with altimetry and tide gauge sea level records in 1990-2003. Despite of the improvement in the climatological salinity, GODAS seriously underestimates salinity variability. Similar to RA6, the equatorial currents contain large errors, which are suspected to be related to the errors in salinity. Another deficiency of GODAS is its mean shift in 1990 (Fig. 1), which is contributed to a sudden increase of number of observations in 1990 when the TAO data became available (Fig. 2). The warm biases in the pre-1990 period have significant influences on the forecast skill of the NCEP's coupled ocean-atmosphere Climate Forecast System, and need to be resolved in the future.

The GODAS ocean analysis is a valuable community asset to monitor different aspects of ocean climate variability. To gain a broader dissemination of GODAS data products, and to increase research community's involvement in the assessment of GODAS and the effectiveness of the NOAA's ocean observing system,



OCO sponsors the CPC to construct a comprehensive

Fig. 1. Differences between temperature of GODAS at 5 meter and Optimal Interpolation SST (Reynolds et al. 2002) averaged in 2°S-2°N.

web site to display the rich information in GODAS. The web site contains numerous images that describe

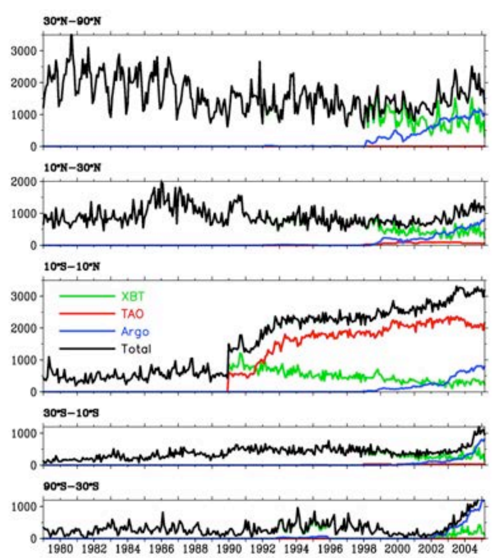


Fig. 2. Monthly counts of temperature profiles used in GODAS in different latitude bands.

not only the SI variability but also the subseasonal variability. Since the goal of the web site is to serve a broad user community that includes operational forecast centers, scientific research groups, and general public, we expect to have frequent communications with users and continue to improve the web site according to the needs of users. The web site can be easily expanded to include other ocean analyses, and give an estimation of uncertainties in the state-of-art ocean analyses.

Addressing NOAA's Program Plan

This project serves to fill in the gap in delivery of ocean analyses as an end product of ocean observations as discussed at the 2005 Annual System Review of the Office of Climate Observation (OCO). This project will facilitate comparisons between model and observation, and help assess the effectiveness of the global ocean observing system.

Responsible Institution

Climate Prediction Center of NCEP is the responsible institution for this project.

Partnerships

This project has been coordinated with the production of the GODAS data sets by the Environmental Modeling Center of NCEP. We are considering possible partnerships with the European Centre for Medium-Range Weather Forecasts (ECMWF) and GFDL on including their ocean analyses in the GODAS web site.

FY 2005 PROGRESS

The GODAS web site contains four components:

- Monthly and annual climatology.
- Monthly anomaly plots and animations from1979 to present (Fig. 3).
- Five-day mean (pentad) anomaly plots and animations from1979 to present.
- Data distributions from1979-present (Fig. 4, and 2).

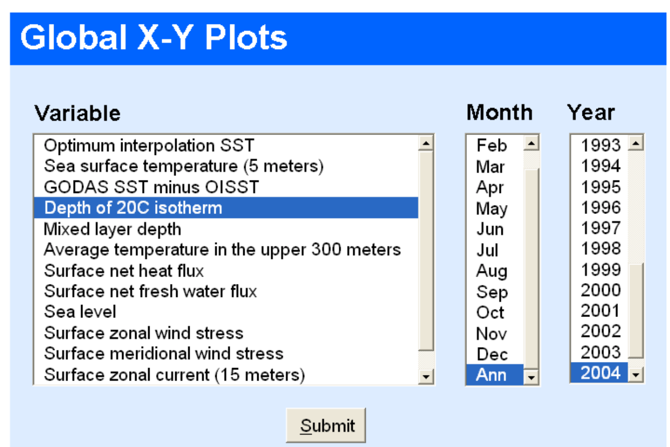


Fig. 3 shows the web page for Longitude-latitude plots where users select variable, month, and year, and then get plots.

The web site contains,

- 2-Dimensional variables such as winds, surface net heat flux, freshwater flux, SST, mixed layer depth, 20ºC isotherm depth, sea level height, heat content of upper 300-meter;
- 3-Dimensional variables such as ocean temperature, zonal current, and meridional current;
- Longitude-latitude maps (Fig.3);
- Longitude-time (hovmoeller) maps (Fig. 1);
- Longitude-depth sections at various latitudes;
- Latitude-depth sections at various longitudes.

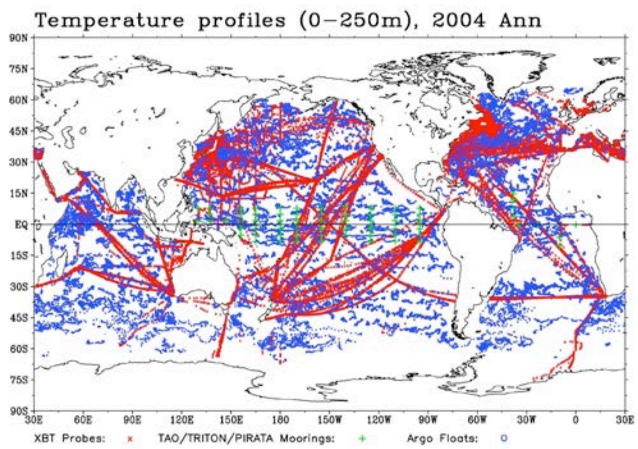


Fig. 4 Distributions of temperature profiles in 2004. XBTs – red, TAO – green, Argo – blue.

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2. Enhanced Ocean Climate Products from NCEP

Stephen J. Lord
NOAA/NCEP Environmental Modeling Center

PROJECT SUMMARY

The NCEP Global Ocean Data Assimilation System (GODAS) runs daily and produces a three-dimensional depiction of the best estimate of the ocean state from all available real-time observations and from information extrapolated forward in time from previous observations using the GFDL Modular Ocean Model, version 3 (MOMv3). Available observations include moored buoys, ARGO floats, sea surface temperature retrievals from satellite imagery, drifting buoys and ship data including XBTs and CTDs. Both temperature (T) and synthetic salinity (S) observations are used in a Three Dimensional Variational (3DVAR) data assimilation technique. The synthetic salinity observations are derived from T-S climatologies for various water masses. GODAS-produced ocean states are used to initialize NCEP's coupled ocean-atmosphere Climate Forecast System (CFS). GODAS output is on 40 levels ranging from 5 meters to 4478 meters.

FY 2005 PROGRESS

Under FY05 funding, codes and scripts were written that allow GODAS archive files to be placed on a NWS public server in WMO standard GRIB format. This capability is now operational and the archive files are available as 5-day averages at
http://cfs.ncep.noaa.gov/cfs/godas/pentad
and as monthly averages at
http://cfs.ncep.noaa.gov/cfs/godas/monthly

Ongoing work focuses on three following three areas: First, we will bring new observational data sets into operational use in the current GODAS; second, we will prepare MOMv4 for new versions of the GODAS and the Climate Forecast System; and third, we will introduce evolutionary improvements into our 3DVAR assimilation system.

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3. National Water Level Program National Water Level Observation Network Annual Report on Sea Level

Stephen K. Gill and Chris Zervas
NOAA/National Ocean Service, Silver Spring, MD

PROJECT SUMMARY

The objective of this project by the NOAA National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is to develop and implement a routine annual sea level analysis reporting capability that meets the requirements of the Climate Observation Program. These data and related sea level products will be made available on the web.

The 10 Climate Operating Monitoring Principles are very much the same as used for the NOAA National Water Level Program (NWLP) for which the National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network

that's strives to meet NOAA's mission needs for tides and water levels. The NWLP is an end-to-end program that is planned, managed, and operated to provide products that meet user-driven needs. The program also consists of technology development, continuous quality control, data base management, and operational readiness and fully open web-site for data delivery.

These data and related sea level products will be made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities.

Routine Sea Level Analysis Reports

A Climate Observation Program Workshop was hosted by the NOAA Office of Global Programs (OGP) May 13 - 15, 2003. The objectives of the workshop were to:

1. Initiate an Annual Program Review
2. Design a framework for regular reports on the ocean's contribution to the state of the climate and on the state of the observing system.
3. Design a framework for implementing Expert Teams to continually evaluate the skill and effectiveness of ocean products and of the observing system.

There are 62 water level stations identified in the International Sea Level Workshop Report (1997) as being part of the core global subset for long term trends. The Climate Observations Program Plan calls these climate "reference stations" and includes the following performance measures for the reference stations.

1. Routinely deliver an annual report of the variations in relative annual mean sea level for the entire length of the instrumental record.
2. Routinely deliver an annual report of the monthly mean sea level trend for the past 100 years with 95% confidence interval.

The Climate Observation Program will be producing an annual report on the state of the ocean and the state of the observing system for climate. CO-OPS will produce an annual report on these reference stations that will serve as one section of that larger report. Over the next 3 years the report will adopt the requirement of including all 62 global reference stations.   The current CO-OPS report on sea level (Zervas, 2001) is being used as a starting template for an annual report.

FY2005 PROGRESS

Routine Sea Level Analysis Reports

CO-OPS began the development efforts for an annual report that includes the 18 NWLON stations listed above. A tailored version of the graphics and analyses from the existing CO-OPS sea level report (Zervas, 2001) has been completed that includes the three fundamental types of analyses where data series allow. The following figures illustrate the types of analyses proposed using Honolulu as an example.

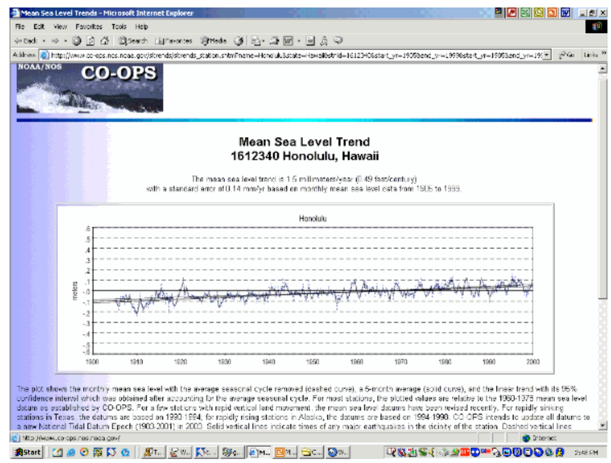

Figure 1. Sea level Trends Analyses would be updated annually.

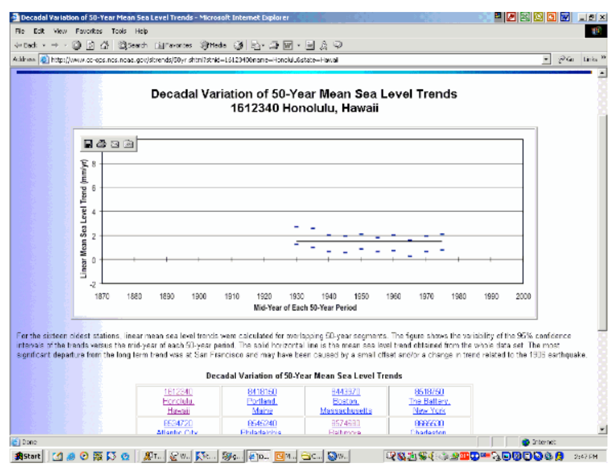

Figure 2. Long-term Variation in Trends would be routinely updated.

Eighteen (18) of the 62 stations are NWLON stations and information about their sea level trends and variations is currently available on the Sea Levels Online section of the CO-OPS website. Sea level analyses

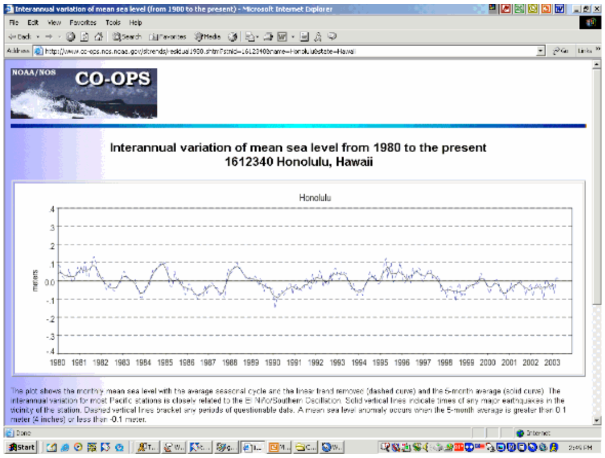

Figure 3. The Monthly Mean Sea Level variations would be updated annually.

have now been completed for the 44 non-NWLON stations. The monthly mean sea level data for these stations were obtained from the Permanent Service for Mean Sea Level (PSMSL) website. The data set obtained was their Revised Local Reference (RLR) data which has been carefully quality-controlled for datum continuity. The 44 stations are:

Station Name	Country	Year Range
Reykjavik	Iceland	45
Narvik	Norway	73
Bergen	Norway	118
Goteborg	Sweden	116
Stockholm	Sweden	114
Helsinki	Finland	122
Daugavgriva	Latvia	66
Liepaja	Latvia	71
Wismar	Germany	155
Esbjerg	Denmark	108
Cuxhaven	Germany	159
Aberdeen	UK	141
North Shields	UK	108
Newlyn	UK	88
Brest	France	193
Cascais	Portugal	111
Marseille	France	115
Genova	Italy	113
Trieste	Italy	96
Tuapse	Russia	85
Tenerife	Spain	72
Takoradi	Ghana	41
Aden	Yemen	90
Mumbai/Bombay	India	116
Vishakhapatnam	India	59
Ko Lak	Thailand	62
Xiamen	China	48
Mera	Japan	70
Aburatsubo	Japan	69
Tonoura/Hamada	Japan	108
Wajima	Japan	69
Manila	Philippines	68
Sydney	Australia	117
Fremantle	Australia	106
Auckland	New Zealand	97
Lyttelton	New Zealand	76
Vancouver	Canada	89
Victoria	Canada	90
Balboa	Panama	88
Quequen	Argentina	64
Buenos Aires	Argentina	82
Cartagena	Colombia	43
Cristobal	Panama	71
Halifax	Canada	107

The 18 NWLON stations available on the CO-OPS Web-site are are (in alphabetical order):

Name:	Series Length (years):
Atlantic City	90
Bermuda	59
Boston	80
Charleston	80
Crescent City	68
Fernandina Beach	104
Guam	53
Hampton Roads	74
Honolulu	96
Ketchikan	82
Key West	88
Kwajalein	55
Neah Bay	67
New York City	144
Pensacola	78
Portland	89
San Diego	95
San Francisco	150

CO-OPS has begun the development efforts for the annual report that includes the 44 non-CO-OPS stations listed above. CO-OPS' Sea Levels Online Webpages are being used as a starting template.

4. In Situ and Satellite Sea Surface Temperature (SST) Analyses

Richard W. Reynolds
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PROJECT SUMMARY

The purpose of this project is to focus on improvements to the climate-scale SST analyses produced at NOAA as described by Reynolds and Smith (1994) and Reynolds et al. (2002). This effort is designed to support the development of an ocean climate observing system. The analysis is done by optimum interpolation (OI) with a separate step to correct any large scale satellite biases relative to the in situ (ship and buoy) data. The analysis uses infrared (IR) satellite data from the Advanced Very High Resolution Radiometer (AVHRR) and in situ data from ships and buoys.

Here we discuss our progress and our plans to improve these analyses. The improvements include the development of better bias corrections, the use of new SST datasets and the development of better error statistics. The largest improvements are related to the change in spatial grid resolution from 1º to 1/4º, the change in temporal analysis period from weekly to daily, and the use of multiple satellite datasets. At this time only an 18 month period has been evaluated using the daily OI. It is planned to refine the new daily analysis including the addition of improved error statistics. In addition, the daily analysis will be made operational and extended backwards in time to 1985.

One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean. During the previous year, we have evaluated the adequacy of the recent in situ network. Because of the high coverage of satellite data, in situ data used in the analysis tends to be overwhelmed by satellite data. Thus, the most important role of the in situ data in the analysis is to correct large-scale satellite biases. Simulations with different buoy densities showed the need for at least two buoys on a 10º spatial grid. This will ensure that satellite biases do not exceed 0.5ºC. Using this criterion, regions were identified where additional buoys are needed, and a metric was designed to measure the adequacy of the present observing system. During the next year, it will necessary to revaluate these results using the daily OI with multiple satellite products.

Richard W. Reynolds is the chair of the SST and sea ice working group which is shared by two GCOS panels: the Ocean Observation Panel of Climate and the Atmosphere Observation Panel of Climate. This proposed work is part of the work of the working group. The working group membership is a broad group of interested national and international scientists. All work presented here follows the Ten Climate Monitoring Principles.

The funds requested for this proposal support work at NCDC. However additional funds at the International Research Institute (IRI) are requested in the added tasks section to support an evaluation of SST analyses using atmospheric models. In addition the National Center for Environmental Prediction (NCEP) runs the weekly version of the OI analysis operationally at no cost to this project. Information on the analyses and the analyzed fields themselves can be found at:
http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/.

FY 2005 PROGRESS

During FY2005, our primary focus has been on OI analysis improvements. This version of the OI analysis (Reynolds and Smith, 1994, and Reynolds, et al., 2002) (henceforth OI.v2) is analyzed weekly on a 1º spatial grid and uses in situ measurements from ships and buoys as well as AVHRR infrared satellite retrievals. As we stated in last year's proposal, we planned to evaluate the OI with improved spatial error covariances and then to add new sources of satellite data to the OI and revaluate the improvements. The final step was to improve the OI temporal and spatial resolution. In the proposal we stated that the impact of the resolution changes "would be modest" when using only one IR satellite dataset. This assumption turned out to be wrong.

Chelton and Wentz (2005) published an article comparing SST analyses including the OI.v2 analysis. In the paper they focused on magnitudes of SST gradients in 6 high gradient regions including the Gulf Stream. These comparisons include intercomparisons of Advanced Microwave Scanning Radiometer - Earth Observing System EOS (AMSR) microwave satellite data with the OI.v2 and the NCEP daily Real Time Global SST (RTG_SST) analysis produced daily on a 1/2º grid (Thiébaux et al., 2003). The RTG_SST analysis uses the same data used in the OI.v2. However, the

RTG_SST has been run daily since 30 January 2001 on a 1/2° grid instead of weekly on a 1° grid and uses smaller spatial error correlation scales than those used in the OI.v2. Chelton and Wentz (2005) showed that the RTG_SST analysis agreed better with AMSR than the OI.v2 even though, as will be discussed below, the AVHRR data is often sparse because of cloud cover. Tests with reduced correlation scales showed that the weekly OI.v2 could not reproduce the sharp gradients shown in the AMSR data and the RTG_SST. Thus, production of a daily OI analysis was given a high priority.

Preliminary Analysis Efforts

The weekly OI analysis method used by Reynolds et al. (2002) includes a preliminary correction of the AVHRR satellite data before it is used in the OI. This is necessary because the OI method assumes that the data do not contain long-term biases. The bias correction uses a Poisson technique to remove satellite biases relative to in situ data before the OI analysis is begun. This method has been used successfully. However, the major problem with this method is that each correction is performed independently at each time step. Thus, there is no time continuity of the correction. In most cases, the cause of the bias, for example the presence of volcanic aerosols, does persist in time. A new method was developed using an OI bias correction. This was done as an analysis of the difference between in situ data and each type of satellite data. To provide continuity in time, the OI bias analysis uses the preceding OI bias analysis as a first guess. This bias correction was initially computed weekly and compared with the Poisson method. Tom Smith (NCDC) computed spatial error correlations and signal to noise ratios. Because the in situ data were noisy, the scales were large and had to be assumed isotropic and homogenous. The scales that worked best were a bias noise to signal ratio (standard deviation) of 4 and spatial error correlation scale of 1500 km. Examination of the results showed that differences between the Poisson bias corrections and the OI bias corrections were modest. However, the OI bias correction is superior because of the time continuity and this correction is used in the daily OI.

The Daily Analysis

To begin the daily analysis, it was first necessary to re-acquire the data, since the original data had not been saved because disk space was more limited 10 years ago. The satellite data that had been used was the operational version produced by the US Navy from AVHRR data (May et al., 1998). However, there were also data from the Pathfinder AVHRR reanalysis project (Kilpatrick, et al., 2001). Pathfinder data have the potential of being better than the operational set, because a re-analysis allows corrections to the AVHRR dataset in a delayed mode. It was decided to use both types of AVHRR data. In addition, AMSR data were obtained from Remote Sensing Systems (RSS) (http://www.ssmi.com) as gridded data for ascending and descending passes on a daily 1/4° grid. The in situ data were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

The 1° OI code was modified to run daily on a 1/4° grid and to allow multiple satellite datasets instead of AVHRR alone. However, for this purpose the OI noise to signal and correlation scales had to be modified. These scales had been computed by Tom Smith for weekly data. He devised a method to adjust these corrections so they could be used for daily data. The modified spatial scales are similar to the 100 - 400 km scales used in the RTG_SST. The weekly OI bias correction required little change. It was modified to use the daily SST data files that were used by the daily OI and then computed daily using the most recent 7 days of data.

The daily OI codes were run for both Pathfinder and operational US Navy AVHRR data for January 2002 - December 2003. In addition, the AMSR data were obtained from RSS and the daily OI was run from June 2002 (the start of AMSR) through the end of 2003. Thus, the following OI daily versions have been completed: AVHRR Pathfinder (January 2002 - December 2003), AVHRR operational Navy (January 2002 - December 2003) and AMSR (June 2002 - December 2003). All analyses include the same in situ data and were run with and without satellite bias correction. As can be expected (e.g., Chelton and Wentz, 2005) the coverage of AMSR data is dramatically improved over AVHRR because microwave data can be retrieved under cloudy conditions as long as there is no precipitation. In particular, the impact of clouds greatly reduces AVHRR retrievals north of 40°N and south of 40°S compared to AMSR.

The Daily Analysis Results

To summarize the results, we first show the monthly average magnitude of the SST gradient in the Gulf Stream region for January 2003 in Figure 1. The RTG_SST and OI.v2 use operational AVHRR data. Thus, we show the daily OI using operational data and the operational data themselves in the first row. The next row shows the OI.v2 and RTG_SST analyses. The final row shows the daily OI using AMSR data and the AMSR data themselves. Figure 1 shows that the daily OI using the operational data is very similar to the

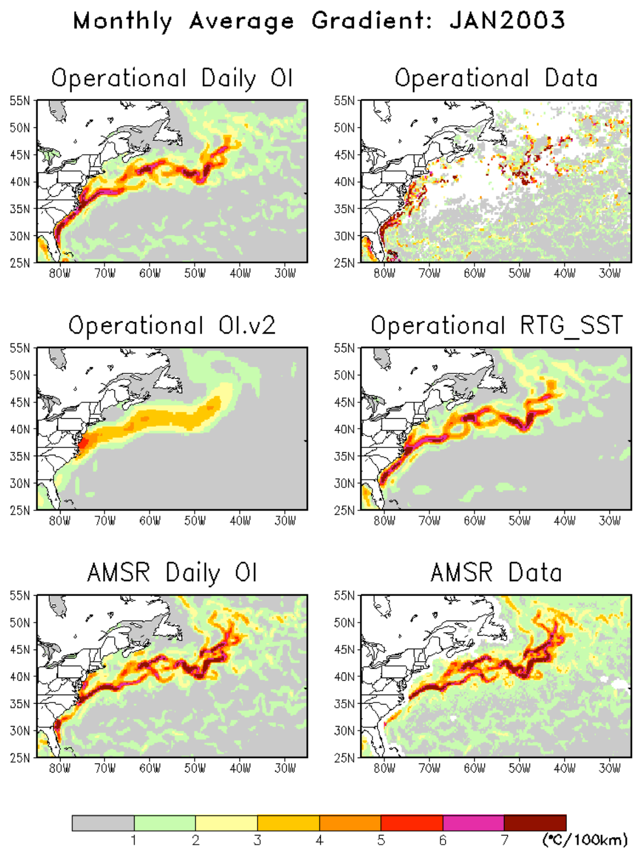

Figure 1. Monthly averaged SST gradient magnitudes for January 2003. The top left panel shows the 1/4° daily OI gradient using operational AVHRR retrievals; the top right panel shows the gradient from the operational AVHRR retrievals. The middle left panel shows the 1° weekly OI.v2 gradient using operational AVHRR retrievals; middle left panel shows the 1/2° NCEP RTG_SST gradient using operational AVHRR retrievals. The bottom left panel shows the 1/4° daily OI gradient using AMSR retrievals; the top right panel shows the gradient from the operational AMSR retrievals.

RTG_SST. However, the gradients in the OI.v2 are strongly smoothed as expected. The operational AVHRR data shows the sparseness of these retrievals. The coverage would be much better in a summer month when the cloud cover is reduced compared to winter. The AMSR data shows much stronger gradients than any of the AVHRR analyses. However, near the coast values are missing because microwave retrievals cannot be made near land. The daily OI using AMSR data shows gradients that are almost as strong as the AMSR data and stronger than any analysis using AVHRR data. At first it may seem surprising that the AVHRR gradients would be as accurate as shown given the sparse AVHRR data. It is necessary to point out that the gradients were computed daily using 4 point centered differences. If any of the four values were missing, the gradient was missing. This tends to exaggerate the impact of any missing data. The results indicate that the daily OI can do a credible job of reproducing SST gradients. Furthermore, a combined analysis using both AVHRR and AMSR would produce the best gradients because AVHRR would add coastal values while AMSR would improve open ocean coverage over AVHRR alone.

We have examined daily gradients for the 4 western boundary regions (Gulf Stream, Kuroshio, Agulhas and Falkland areas) shown in Chelton and Wentz (2005). In these regions the AMSR coverage is almost complete over 3 days. The daily OI using AMSR shows that much of the gradient is stationary over time due to topography. Thus, the daily OI using AVHRR alone can do a credible job of determining the stationary part of the signal with only limited observations during the month. However, in other high gradient regions, e.g., at the northern boundary of the cold water tongue in the eastern tropical Pacific, the gradients are progressive and cannot be analyzed properly under persistent cloud cover.

Differences between the OI analyses using the different satellite products show that satellite bias corrections are needed for each product. Figure 2 shows the 18 month average difference between the daily OI using Pathfinder and operational AVHRR with and without bias correction. The analysis difference without bias correction (top panel) shows that Pathfinder is cooler in the tropics than the operational Navy product. These differences lie along regions of persistent cloudiness such as the Intertropical Convergence Zone and the South Pacific Convergence Zone. This suggests clouds may contaminate some of the Pathfinder retrievals. Comparisons of the number of observations, not shown here, also indicate an increase in the number of Pathfinder observations compared to the Navy product. The differences along 60°S are due to a problem with the Navy operational product. When the Navy moved from NOAA-16 to NOAA-17 in the spring of 2003, a low stratus cloud test, which worked well for NOAA-15 and NOAA-16, was continued for NOAA-17. However, this test actually limited the coverage and was eliminating too many good SSTs. The test was corrected on August 24, 2004 (Dan Olszewski, personal communication, 2005). The analysis difference with bias correction (bottom panel) shows that almost all the large scale differences have been corrected although a small residual remains in the tropical Pacific along 10°N and in the South Pacific along 60°S.

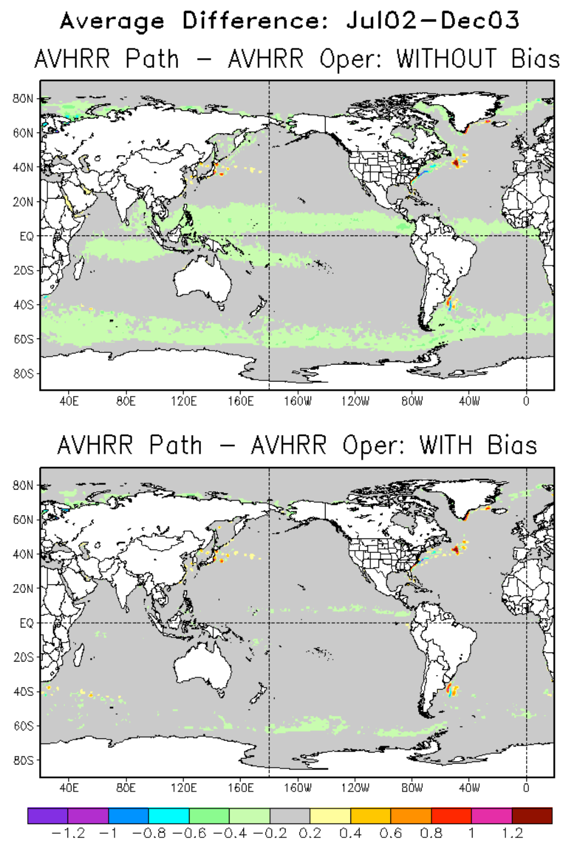

Figure 2. The average daily 1/4° OI anomaly difference between AVHRR Pathfinder and AVHRR operational for the 18 month period: July 2002 - December 2003. The top panel shows the difference when both sets of satellite retrievals WERE NOT biased corrected before being used in the OI. The bottom panel shows the difference when both sets of satellite retrievals WERE biased corrected before being used in the OI.

Figure 3 shows a similar comparison of the 18 month mean difference between the daily OI using Pathfinder AVHRR and using AMSR. The tropical differences without bias correction (upper panel) again suggest cloud contamination of the Pathfinder product. However, since the differences are stronger than those shown in Figure 2 and are spatially similar, this suggests that clouds may contaminate both AVHRR products. In the tropical North Atlantic, dust from the Sahara Desert is blown toward the west and frequently causes negative AVHRR biases particularly in the summer. This appears to be an explanation of some of the differences shown in the Atlantic between the equator and 20°N. Smaller differences of both signs occur north of 40°N and south of 40°S and are difficult to explain. The bias corrected difference (bottom) panel shows that the large-scale tropical differences have been reduced by roughly 1/2 to 1/3 of the uncorrected differences. Similar large scale reductions have occurred with bias correction north of 60°N. However, south of 40°S the bias correction had little impact. This is most likely due to the smaller north/south scales of the differences shown in Figure 3 than shown in Figure 2. Please recall that our e-folding scale for the bias corrections is 1500 km or roughly 13.5°. Thus, corrections on scales smaller than the e-folding scales are difficult. Between 30°N and 40°N, the results are mixed. There is some reduction of the differences with bias correction except off the east coast of the US between Florida and North Carolina where they get worse. This will have to be investigated. However, we think it may be due to using the lower resolution OI.v2 climatology instead of a higher resolution version before differences were computed. Because there are large gradients in this region (see Figure 1), SST changes may be large over relatively small distances.

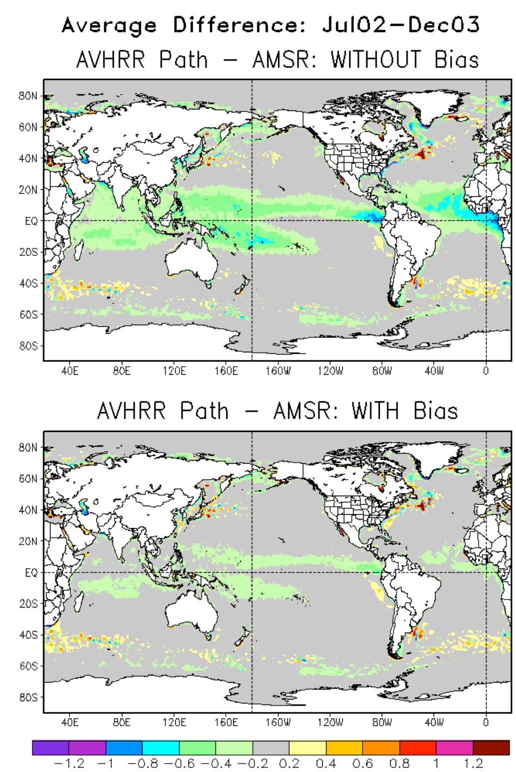

Figure 3. The average daily 1/4° OI anomaly difference between AVHRR Pathfinder and AMSR for the 18 month period: July 2002 - December 2003. The top panel shows the difference when both sets of satellite retrievals WERE NOT biased corrected before being used in the OI. The bottom panel shows the difference when both sets of satellite retrievals WERE biased corrected before being used in the OI.

Design of an in situ SST network to improve the SST analysis

During the preceding years, we designed an in situ network to correct "potential satellite bias errors." This network was determined using the weekly OI.v2 with simulated biased satellite retrievals and simulated unbiased buoy data. The maximum "potential satellite bias error" was selected to be 2°C as a worse case. Thus, the "potential satellite bias error" would be 2°C if there were no in situ data to correct the bias. The data density of the present in situ network was evaluated to determine where more buoys are needed. These buoys could be either moored or drifting. However, because of the high cost of moored buoys they will be assumed to be drifters. To reduce the potential satellite bias to below 0.5°C, a buoy density of about 2 buoys/10° grid is required. The present in situ SST observing system was evaluated to define an equivalent buoy density (EBD), allowing ships to be used along with buoys according to their random errors. An example is shown in Figure 4 for April-June 2005. The figure shows a clear need for additional buoys in the middle latitude Southern Hemisphere oceans. These figures are produced seasonally and are used to guide surface drifting buoy deployments. For more details see Zhang et al (2005).

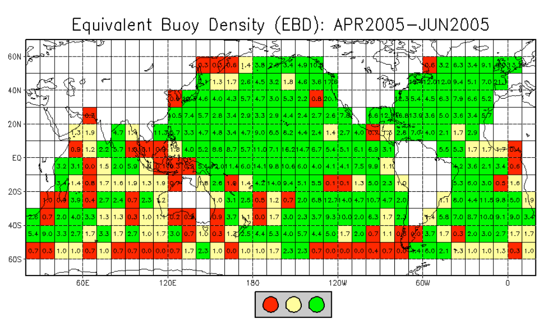

Figure 4. Seasonally (April – June 2005) averaged monthly equivalent buoy density (EBD) on a 10° grid. EBD includes contributions from both buoys and ships, accounting for their typical random errors. Green shading indicates where EBD≥2 and no more buoys are needed. Red shading indicates critical regions where EBD<1 and two more buoys are needed. Yellow shading indicates 1≤EBD<2 where one more buoy is needed.

5. Investigating Some Practical Implications of Uncertainty in Observed SSTs

Lisa Goddard

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PROJECT SUMMARY

The purpose of this task is to evaluate the impact of uncertainty in observed SSTs on seasonal-to-interannual prediction. One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean. The activities described here are intended to provide feedback to the climate observing community on the apparent impact of that improvement for seasonal climate simulations and predictions.

The activities under this task are two-fold:

(1) Estimate the impact of SST uncertainty, as estimated by added information from satellites, on climate simulations from AGCMs. This is done by running an atmospheric general circulation model (AGCM) over a set of years with two different analyses of the observed SSTs: one that includes satellite data (OIv2) and one that does not (ERSSTv2). The questions being addressed are, "Is the simulation with satellite SST data more representative of the observed climate?", and "Are there any detectable systematic, SST-related differences between the simulations"?. This activity is in progress.

(2) Evaluate what maximum skill should be expected from SST predictions given uncertainty in the "truth." This will be estimated verifying the observed time series of SSTs against the same time series including a normally distributed error that is either fixed at 0.4 degC (FY06 target), or that is spatially and temporally varying according to the estimated sampling error of the ERSSTv2 data. The results from this activity are consistent with the sampling analysis of Reynolds (see Figure 4 from Reynolds FY05 Progress Report), indicating important regional gaps in the SST observing system. This preliminary analysis suggests that SST uncertainty in those regions, particularly those in the tropics, are likely to have a discernible influence on the boundary-forced climate.

FY 2005 PROGRESS

AGCM Sensitivity Experiments

We already have historical simulations of the ECHAM4.5 AGCM (T42,L18) forced with OIv2 data over the 1982-2003 period. We have set up another simulation using the ECHAM4.5 model forced with ERSSTv2 data for the same period. An ensemble of 20 members is being run, differing only in their initial conditions, which are taken from on-going long runs of the model. We anticipate that the runs will be completed by the end of November 2005. We will then analyze the results and communicate findings to OCO, as well as report results in a journal article.

SST Potential Predictability Estimates

The results from activity (2) are consistent with the sampling analysis of Reynolds (see Figure 4 from Reynolds FY05 Progress Report). Figure 1 shows the expected predictability limit, as measured by correlation, for the ERSSTv2 data. In the upper panel, a fixed error variance, or uncertainty, is assumed of 0.4deg.C, which is the stated FY06 target for SST accuracy. In the lower panel, a spatially and temporally varying error is given by the sampling error variance[6] estimated for the ERSSTv2 data. Clearly the areas of relatively low correlation reflect low sampling, or equivalently high sampling error, which explains the resemblance between this analysis and that of Reynolds-Figure 4. An important aspect to notice in the similarity between the two figures is that Reynolds-Fig4 is presented for a single, recent 3-month season, while Figure 1 summarizes 20+ years of data. In other words, the SST sampling gaps are geographically persistent.

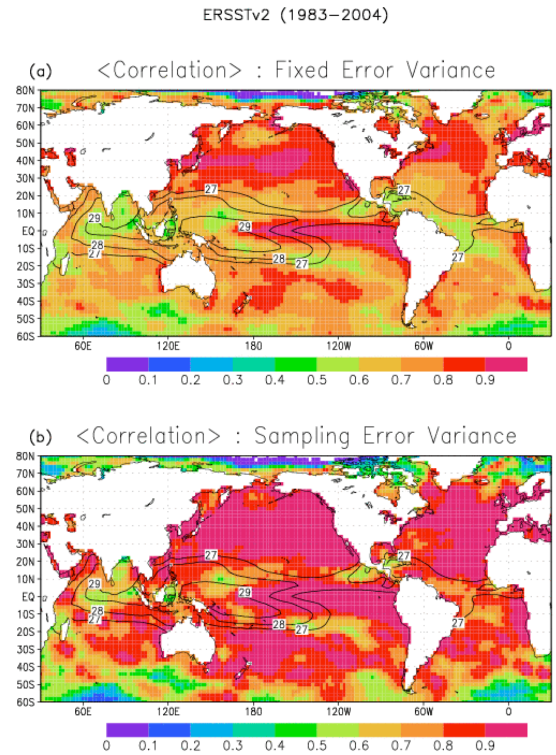

Figure 1. Correlation between observed time series, taken as "truth", and that timeseries with random Gaussian error described by assumed error variance. (a) Error variance assumed fixed at 0.4 deg.C, which is the FY06 target for SST accuracy. (b) Error variance taken from estimated sampling error variance of the ERSSTv2 data. Superposed black contour indicates climatological SST at 27, 28, 29 deg.C, demarking the warmest and most convective regions of the tropics

The proximity of the low skill areas to the warm pool and other convergence regions (shown by heavy black contours on Figure 1) in part explains their existence. Where the SST is relatively warm, low-level convergence and convection exists in the vicinity. The clouds resulting from the convection hamper the IR satellites from accurately measuring SST. The implications of the low skill regions for simulating the climate with AGCMs is that an incorrect representation of changes in these fringe areas of the warmest SST regions can adversely affect the spatial representation of SST anomalies, altering the strength and location of convection and associated upper and lower tropospheric flow.

A related point is that SST skill maps from CGCMs (e.g. Figure 2) are roughly consistent with the regions of lower potential predictability or verifiability (Figure 1). This use of the term 'potential predictability' refers to our knowledge of the true observation, for which improvement can be made (see Reynolds FY2006 plans). This differs from the more common usage of 'potential predictability', which typically refers to an inherent limitation in the accuracy obtainable from a forecast, and is related to disentangling the signal from the noise. In the case of the CGCM, both aspects of potential pre

[6] According to Smith and Reynolds (2004), the total error variance associated with the local SST is dominated by the sampling error variance.

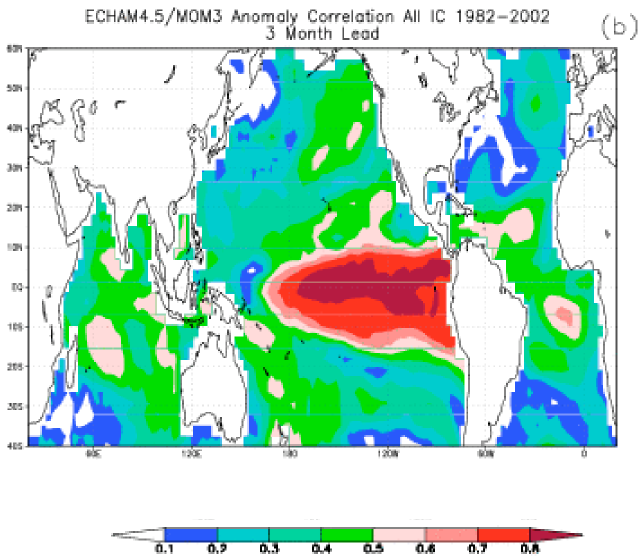

Figure 2. Anomaly correlation between 3-month lead CGCM forecast SSTa and observed SSTa from OIv2. (Courtesy D.G. DeWitt, IRI)

dictability are limiting the accuracy of the forecasts. However, since the uncertainties in the SSTs suggest that an upper limit of skill should be something similar to what is shown in Figure 1, it could be argued that SST predictions should present skill results relative to such an upper limit and explicitly account for the uncertainties in the verification data.

Implications for the AGCM sensitivity experiment emerge through comparison of expected skill limit for the ERSSTv2 data (Figure 1b) and the ERSSTv2 versus OIv2 correlation (Figure 3). Since the correlation be-

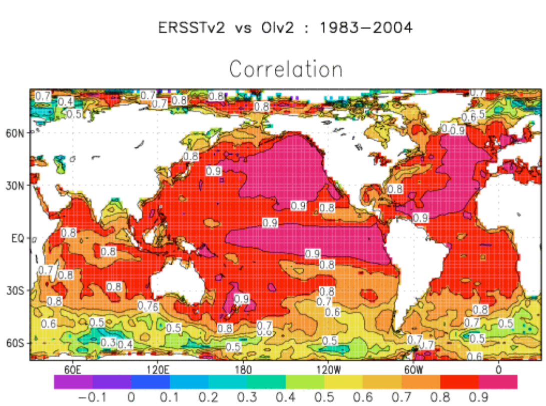

Figure 3. Anomaly correlation between two observed datasets: ERSSTv2 (in situ data only) and OIv2 (in situ + satellite data).

tween the two datasets is higher than the 'expected maximum skill' from a single dataset, the AGCM experiment will not tap the full magnitude of SST uncertainty. This suggests there may be common errors between the two datasets that just haven't been quantified for OIv2, or possibly that the error variances are overestimated for parts of the tropics in ERSSTv2.

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6. A Fifty-Year Analysis of Global Ocean Surface Heat Flux

Lisan Yu and Robert A. Weller
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PROJECT SUMMARY

Air-sea flux exchange is the single most important process in air-sea interaction. Virtually all the hypotheses to explain coupled ocean-atmosphere variability on climate timescales involve surface fluxes as a key link. Surface heat fluxes with not only high quality but also consistent, long climate record have long been sought to establish air-sea feedback mechanisms, provide guidance and motivation for modeling studies, verify individual or coupled atmosphere-ocean general circulation model simulations, and serve as forcing functions for ocean model exercises. The three useful data sources that the estimation of surface heat fluxes is dependent of include ship meteorological reports, satellite retrievals, and numerical weather prediction (NWP) model outputs. However, all three sources are plagued by at least one of the four deficiencies: (1) incomplete in situ data coverage, (2) short spanning period, (3) systematic bias, and (4) random error. While improving the quality of each data source is essential, this project takes an alternative approach, i.e., to produce a synthesized flux product with improved resolution and improved quality through synthesizing the advantages of the three data sources.

The main objective of the project is to develop gridded air-sea heat flux fields (including latent and sensible heat loss and shortwave and longwave radiation) over the global ice-free oceans for the past 50 years. The project addresses NOAA's Program Plan for *Building a Sustained Ocean Observing System for Climate* by providing quality estimation of air-sea heat exchanges to assist the assessment of global transport of heat and freshwater and the ocean's storage and help understanding long term trends in global sea surface temperature and upper-ocean heat content changes. The project research can also be used to assist implementation panels on designing moored buoy array location. In YR2005 the project has analyzed spatial and temporal characteristics of air-sea heat fluxes in the Indian Ocean and provided the reference for the international CLIVAR Indian Ocean Implementation panel for the evolving design of a sustained observing system for the Indian Ocean.

More information on the project and the project products can be found from the website at http://www.whoi.edu/science/PO/people/lyu/resflux.html.

FY2005 PROGRESS

Data products

We have produced turbulent latent and sensible heat fluxes over the global ice-free oceans (65°S – 65°N) with 1°×1° degree, daily resolution for the years of 1980 onward. The development of these daily flux fields is based on the following two procedures. First, the estimates of the flux-related surface meteorological variables (i.e., wind speed, specific air humidity, air temperature, and sea surface temperature) are obtained from a synthesis process using a variational objective analysis. The input data for the synthesis include satellite retrievals and also outputs of NWP models, i.e., the European Centre for Medium-Range Weather Forecasts (ECMWF) operational forecast model, ECMWF Re-Analysis 40 (ERA40), and the National Centers for Environmental Prediction (NCEP) reanalysis–forecast model. Second, the flux-related variables determined from the synthesis are applied to the TOGA COARE bulk flux algorithm 2.0 (Fairall et al. 1996; Bradley et al. 2000) to compute the latent and sensible heat fluxes. Considerable efforts have been put into the preparation of the input data used in the synthesis, because the flux-related variables from NWP models have large biases. Bias correction is made to all NWP variables by using in situ buoy and research vessel measurements of surface meteorology. More than 100 time series of in situ observations have been used in the bias correction effort.

Together with the global net surface radiations (3-hourly, 2.5° grid) from ISCCP-FD dataset from July 1983 to June 2001, we have constructed 18 years of global daily net surface heat flux fields (i.e., the sum of turbulent latent and sensible heat fluxes and net shortwave and longwave radiations). The Atlantic part of this dataset has been made public and can be downloaded from ftp://ftp.whoi.edu/pub/users/lyu/flux. Effort is underway to make the global dataset online.

Analysis and research highlights

We have conducted analyses of mean and variability of air-sea heat fluxes and the role of heat flux in basin-scale atmosphere-ocean interactions using the newly developed flux product. In FY2005 four referred papers have been published/submitted. Highlights of two of these publications are given below.

1) The methodology and validation of the OAFlux product developed by us at WHOI was published in the Journal of Climate 2004. The abstract reads "the study focused on analyzing the mean field properties of the WHOI daily latent and sensible fluxes and their comparisons with the ship-based climatology from the Southampton Oceanographic Centre (SOC) and with NWP outputs. It is found that the WHOI yearly-mean fluxes are consistent with the SOC climatology in both structure and amplitude, but the WHOI yearly-mean basic variables are not always consistent with SOC; the better agreement in the fluxes is due to the effects of error compensation during variable combinations. Both ECMWF and NCEP2 have larger turbulent heat loss (~ 20 W m^{-2}) than the WHOI product. Nevertheless, the WHOI fluxes agree well with the NCEP2 reanalysis fluxes in structure and the trend of year-to-year variations, but not with the ECMWF operational outputs; the latter have a few abrupt changes coinciding with the modifications in the model forecast/analysis system. The degree of impact of the model changes on the basic variables is not as dramatic, a factor that justifies the inclusion of the basic variables, not the fluxes, from the ECMWF operational model in the synthesis. The flux algorithms of the two NWP models give a larger latent and sensible heat loss. Recalculating the NWP fluxes using the COARE algorithm reduces considerably the strength but does not replicate the WHOI results. The present analysis could not quantify the degree of improvement in the mean aspect of the WHOI daily flux fields as accurate basin-wide verification data are lacking. *This study is the first to demonstrate that the synthesis approach is a useful tool for combining the NWP and satellite data sources and improving the mean representativeness of daily basic variable fields and hence the daily flux fields. It is anticipated that such an approach may become increasingly relied upon in the preparation of future high quality flux products.*"

Yu, L., R. A. Weller, and B. Sun, 2004: Improving latent and sensible heat flux estimates for the Atlantic Ocean (1988-1999) by a synthesis approach. J. Clim., 17, 373-393.
http://www.whoi.edu/science/PO/people/lyu/pdfs/YU-atlflx-dailymap-jc04.pdf

2) We have contributed a study of surface heat flux variability in the Indian Ocean to the Journal of Climate special issue on the CLIVAR Indian Ocean Climate Variability. As stated in the abstract, "The study found that the mean pattern of the six products differs considerably for the analysis period of 1988-2000. The two analyzed flux products from OAFlux+ISCCP and SOC show that the Indian Ocean, north of 15°S gains heat on the annual mean basis, while the four numerical model prediction (NWP) products from NCEP and ECMWF show that the Indian Ocean including the northern basin is a heat loss region. Validation of the six products with time series of in situ flux measurements obtained in the Arabian Sea and Bay of Bengal indicated that the four NWP fluxes underestimated the magnitude of the net heat flux into the ocean and all have a sign opposite to in situ measurements in the Bay of Bengal. OAFlux+ISCCP is in agreement with the SOC analysis and has the best comparison with in situ measurements. The accuracy in the southern basin remains to be assessed due to the lack of verification datasets. "

Yu, L., X. Jin, and R. A. Weller, 2005: Annual, seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean. Journal of Climate. Submitted. http://www.whoi.edu/science/PO/people/lyu/pdfs/YU-ioflx-jc05.pdf

In addition to these two studies, we have also analyzed the role of air-sea heat flux in seasonal variations of SST in the tropical Atlantic Ocean. The two findings are that (1) the net surface heat flux is a primary forcing for the annual cycle of SST in the regions poleward of 5°S and 5°N and away from the coasts; and (2) the net surface heat flux produced by OAFlux+ISCCP is consistent with subsurface observations in depicting the mixed layer thermodynamics as governing mechanisms of seasonal variability of SST over most of the tropical Atlantic. The analysis projected two belt regions that SST is controlled by oceanic processes: one belt is along the equator and the other is off the equator between 3°N and 10°N. The study suggests that the improvement made in the heat flux estimation certainly enhances the physical representation of the dataset and enhances the understanding of the primary role of surface heat flux in SST variability on seasonal and longer time scales.
http://www.whoi.edu/science/PO/people/lyu/pdfs/YU-atl-nflxSST-jc05.pdf

The analysis of the change of surface heat flux in the Indian Ocean leads to the finding of an upward trend in latent heat loss over the past two decades. The latent heat loss is in response to the basin-wide warming of sea surface. The mechanisms responsible for the SST warming under the condition that the net heat flux in the basin has not been increased are investigated.
http://ams.confex.com/ams/Annual2006/techprogram/paper_104821.htm

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7. Climate Variability in Ocean Surface Turbulent Fluxes

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PROJECT SUMMARY

This project supports development of an objective system for gridding monthly in situ observations and daily hybrid satellite and NWP observations. The surface winds in these products have been widely used in ocean modeling and ENSO prediction. We also produce fields of surface turbulent fluxes, and the variables needed to calculate these fluxes. Ocean surface forcing fields, with objectively derived uncertainties, are well suited to aid in understanding the global climate system and hence in climate prediction. Our long-term monthly fields are well suited for seasonal to decadal studies, and our hybrid satellite and numerical weather prediction (NWP) fields are ideal for weekly to annual variability and quality assessment of the monthly products. These products will continue to be made freely available.

Predictions of ENSO phase and its associated teleconnection anomalies could be extremely useful to the agricultural community. Agricultural decisions in the southeast U.S. sector based on ENSO predictions could benefit the U.S. economy by over $100 million annually (Adams et al., 1995). A similar, more recent estimate for the entire U.S. agricultural production suggests economic value of non-perfect ENSO predictions to be over $240 million annually (Solow et al., 1998). These impacts could easily be extended to other economic sectors, adding further economic value. Moreover, similar economic value could be foreseen in other world economies, making the present study valuable to the global meteorological community.

ENSO, PDO, and NAO (AO) each have atmospheric and oceanic components that are linked through the surface of the ocean. Years of study have revealed ENSO to be a fully coupled ocean-atmosphere system. Changes in the upper ocean circulation result in modifications to the SST and near surface wind patterns. Variations in SSTs can be related to ENSO, PDO, NAO (AO), and the Indian Ocean dipole; however, it is the fluxes of heat and radiation near the ocean surface that transfer energy across the air-sea interface. It is an improved understanding of these turbulent fluxes and their variability that motivates our research (radiative fluxes are difficult to accurately estimate from in situ data; however, satellite-based estimates are available). By constructing high quality fields of surface fluxes we provide ourselves the improved capabilities to investigate the energy exchange at the ocean surface. The flux related variables (winds, SST, near surface air temperature, near surface humidity, and surface pressure) are also useful for ocean forcing (e.g., Morey et al. 2005a,b), testing coupling in coupled ocean/atmospheric models, and for climate related variability (Raulerson et al. 2005). For example, monthly Atlantic Ocean surface pressures have been found to be a good indicator of extreme monthly mean temperatures in Florida (Raulerson et al. 2005).

Identifying climate scale variability in ocean surface turbulent fluxes expands on existing needs by the ocean/atmospheric modeling community for high quality flux fields. Current options for global flux fields are limited. Products derived by global analysis centers (e.g., NCEP, ECMWF) have large biases and uncertainties both regionally (e.g., Bony et al. 1997, Renfrew et al. 2000) and globally (e.g., Smith et al. 2001). The flux parameterizations used in these reanalyses are not consistent with state of the art flux models (Brunke et al. 2001; Curry et al. 2004). Furthermore, the there are substantial biases in the parameters used to calculate fluxes (Smith et al. 2001). Satellite derived products (Atlas 1996; Pegion et al. 2000; Morey et al. 2005a) are temporally limited and thus of limited use for studies of phenomena with long periods. Similarly, an excellent new monthly flux product that combines in-situ and a few satellite observations (Josey et al. 1999) spans an insufficient period for interdecadal studies. One of our goals is to produce objective fluxes and related fields that have the accuracy and the spatial and temporal coverage required for examining seasonal to decadal variability.

The study of climate variability is further complicated because variability on scales <3 days and 25-500 km influences the long term state of the ocean, and hence changes of the variability on these scales influences the climate. Recent studies (Bourassa et al. 1999, 2005; Wentz et al. 2000; Chelton et al. 2001) have shown that modern satellite coverage can be used to examine SST, wind, and stress variability on the scale of roughly 200 km and several days. The tools required to create research-quality gridded fields on these (and finer) scales now exits (Pegion et al. 2000; Bourassa et al. 2005; Morey et al., 2005a,b), as do the satellite observations and the ocean models required to study the impacts.

The flux project at FSU targets the data assimilation milestones within the Program Plan. Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the air-sea exchange of heat, momentum, and fresh water. When the FSU products are combined with ocean models (either at FSU or other institutes), performance measures relating to surface circulation and ocean transports can be addressed. The FSU flux project also focuses on the task of evaluating operational assimilation systems (e.g., NCEP and ECMWF reanalyses) and continues to provide timely data products that are used for a wide range of ENSO forecast systems.

All development of the objective flux system and operational production of the FSU winds and fluxes are the responsibility of COAPS. Our satellite partners include Gary Wick (NOAA-ETL; satellite SST), Frank Wentz and Deborah Smith (Remote Sensing Systems; scatterometer winds, passive microwave scalar winds, passive microwave SST), and Bill Rossow and Yuanchong Zhang (NASA; radiative fluxes). We maintain a long-term collaboration with Dr. Jacques Servain (IRD, France) who focuses on data and products for the tropical Atlantic Ocean. We also continue to collaborate with U. S. and international partners in the CLIVAR program, SEAFLUX, and GODAE to provide the wind and flux products needed to achieve these projects' goals. Additional development and scientific analysis of the FSU fluxes is supported by NSF Ocean Sciences and base funding for COAPS is provided through a NOAA

Applied Research Center. NASA has also been a partner in the development of satellite based fields. All the FSU wind (and eventually flux) products are freely available at: http://www.coaps.fsu.edu/RVSMDC/SAC/.

The FSU flux project began managing its operation in accordance with many of the Ten Climate Monitoring Principles long before they were spelled out by the GCOS (2004). We continue to fully document and provide free access to all of the FSU wind and flux products. We endeavor to maintain a consistent product over many years and are careful to include parallel testing whenever possible before changing analysis methods. When a former product is discontinued, we provide a comparative assessment of the new and old products to aid the users transition (e.g., Bourassa et al. 2005).

FY 2005 PROGRESS

An objective analysis technique (Bourassa et al. 2005; Morey et al. 2005a,b) has been developed to produce fields of surface turbulent fluxes (momentum, latent heat, and sensible heat fluxes) and the fields used to create the fluxes (vector wind, scalar wind, near-surface air temperature and humidity, and SST). This approach treats the various types of observations (volunteer observing ships (VOS), moored buoys, drifting buoys, different satellites) as independent, and objectively determines weights for each type of observation. The flux project at FSU targets the data assimilation milestones within the Program Plan (NOAA 2005). Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the air-sea exchange of heat, momentum, and fresh water. The accuracy of the momentum and heat fluxes of the satellite products have been examined indirectly via forcing ocean models (Morey et al. 2005a,b) and found to be excellent.

The in situ momentum fluxes have been validated in comparison to monthly averaged scatterometer forcing (Bourassa et al. 2005) and found to be remarkably similar to the satellite-based forcing. The 2x2° FSU2 and the subjective FSU product for the Equatorial Pacific Ocean have been compared to monthly averages of scatterometer (NSCAT and QSCAT) pseudostress analyzed on the same grid as the FSU2 winds. Scatterometer winds are the best available standard of comparison. The comparison times are Oct. 1996 through June 1997 for NSCAT, and Aug. 1999 through Dec. 2003 for QSCAT. The comparison to scatterometer data includes mean differences (biases) as well as standard deviations (Fig. 1), which are more indicative of seemingly random differences. These standard deviations are much greater in the comparisons with the subjective FSU winds. The standard deviations for the subjective FSU product have local maximums around the ITCZ and the SPCZ. These shortcomings related to the SPCZ are likely due to the use of 10° longitudinal bins in the hand analysis. The FSU2 also has remarkably improved accuracy in the western Pacific Ocean. Presumably the good quality of the FSU2 winds extends as far back as there are adequate in situ observations. Degradation in quality with time can be examined in future studies if in situ data from the scatterometer time period can be subsampled to simulate coverage during earlier times.

In-situ surface wind and flux products

The objective method (Bourassa et al. 2005) continues to be applied to create two-degree tropical Pacific Ocean wind (pseudo-stress) fields based on in-situ data. Quick-look two-degree gridded pseudo-stress fields are produced at the beginning of each month using the previous month's GTS-transmitted data, and a research product for the preceding year is produced each summer using delayed-mode GTS data from NCDC. At the time of this report, the production of the 2004 Pacific research project has been delayed by problems that were discovered in the data files received from NCDC in June 2005. NCDC has promised repaired files by September 2005, but they have yet to be received by FSU. In the future we anticipate switching from NCDC to ICOADS data products once ICOADS delayed mode updates occur on a yearly basis.

In addition to the Pacific, COAPS continues to produce one-degree pseudo-stress fields for the tropical Indian Ocean using the method of Legler et al. (1989). A switch to produce Indian Ocean fields with the Bourassa et al. (2005) method is anticipated at the start of 2006. Both two-degree fields for the Pacific Ocean and one-degree fields for the Indian Ocean FSU winds are available at

http://www.coaps.fsu.edu/RVSMDC/SAC/index.shtml. Objective Pacific winds (known as the FSU2) are available for 1978-2003 (research) and Jan. 2004 - Sept. 2005 (quick-looks). Indian Ocean winds are available for 1970-2003 (research) and Jan. 2004- Sept. 2005 (quick-looks).

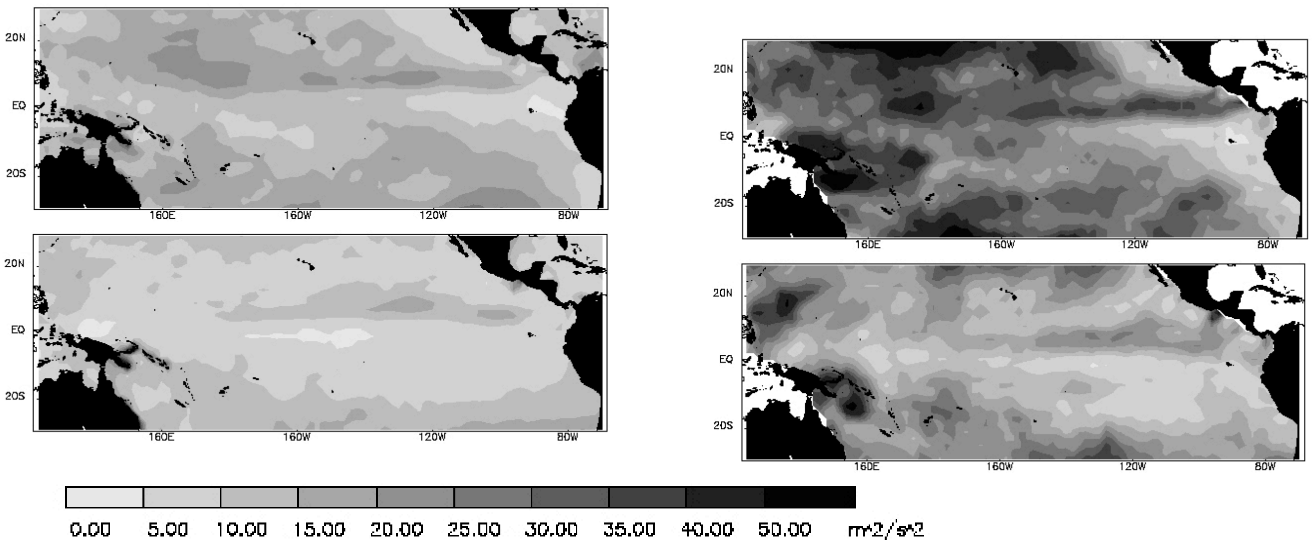

Fig. 1 Standard deviations of monthly differences of FSU and scatterometer pseudostress components, where zonal pseudostress is on the top row and meridional pseudostress is on the bottom row. The new objective FSU winds (left) are much more similar to the scatterometer winds than the old subjective FSU winds (right). The meridional standard deviations have a local maximum about the ITCZ and in the area of the SPCZ. The VOS observation pattern is easily identifiable in the subjective FSU winds

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Development of a higher quality 1°x1° in situ based product (which was requested by users of our products) proved to be much more complicated than expected. We overcame the following problems:

1. Differences between the uncertainty of moored and drifting buoy winds,
2. For finer spatial/temporal resolution products, sampling-related differences in observing systems are more apparent,
3. Near coastal features need to be much more finely resolved,
4. For the Pacific basin, working with 1°x1° binned data resulted in too much data to be manually quality controlled.

The first three problems were particularly evident near coastlines, in archipelagos, and near TAO buoys. These problems have been resolved through five modifications to our approach:

1. We now treat moored and drifting buoys as separate types of platforms,
2. The distance of influence of buoy observations has been reduced,
3. Hourly buoy data are combined into a daily average, and treated as one observation,
4. The area of spatial averaging near coastlines has been reduced,
5. Automated quality control has been developed for gridded observations.

The fifth solution has resulted in a tremendous savings in man-hours.

One degree gridded wind (pseudo-stress) products have been completed for 1978-2003 for the Indian and Atlantic Oceans. These products will be made available on our web and ftp sites once necessary graphical display development has been completed (early in 2006).

We have made great progress towards completing surface turbulent flux fields for the Atlantic and Indian Oceans, and completing uncertainty fields for winds are currently our top priority. Our collaborators have completed radiative fluxes. We will be able to combine these with our products to have the full surface heat flux budget. We are now generating preliminary flux fields. Figure 2 is an example latent heat flux from June 1986 for our Indian Ocean region. Enhanced latent heat fluxes related to the Indian monsoon are evident. Fields of fluxes are also being produced for the equatorial and North Atlantic Ocean for the period 1978 to 2003.

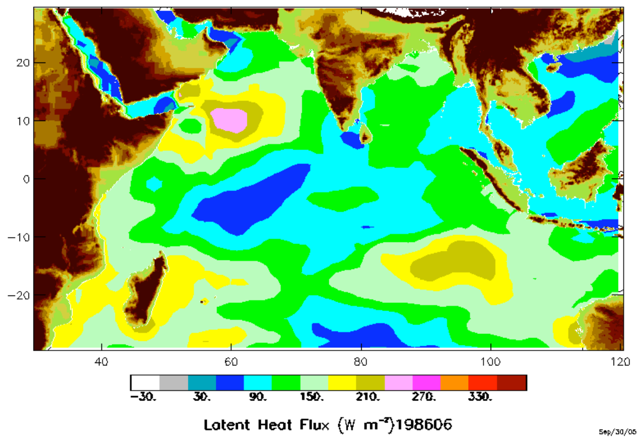

Figure 2. Latent heat flux from June 1986 for the Indian Ocean region.

Satellite surface wind and flux products

Development of our satellite-based products continues. We can now produce fields on an arbitrarily fine spatial resolution. We take advantage of this utility when examining fine structure, usually within observational swaths. Currently, we have two areas of application. We are using such fields to examine the transition of tropical cyclones to extratropical cyclones (Maue 2004), as well as sub-tropical cyclones to tropical cyclones. We are also testing the heat flux in the West Florida Shelf. We have chosen this region because the wide area of shallow water is extremely sensitive to wind (Morey et al. 2005a) and thermal forcing (Morey et al. 2005b). We have developed code for ingesting wind speed data from SSMI, TMI, and AMSR. We have also nearly completed work on the uncertainty of the wind fields. For global gridded fields the uncertainty is dominated by sampling issues. It is only for fine spatial resolution, high temporal resolution fields within swaths that the observational uncertainty dominates the uncertainty in the gridded output.

Currently available products are:

- Daily average pseudostress fields:
  http://www.coaps.fsu.edu/scatterometry/Qscat/gcv_glob_L2B_1x1.html
- Monthly global 1x1 fields:
  http://www.coaps.fsu.edu/scatterometry/Qscat/gcv_glob_L2B_1x1_mon.html
- 12-hourly fields for the Gulf of Mexico
  http://www.coaps.fsu.edu/scatterometry/Qscat/gcv_glob_L2B_hlfxhlf_GofM.html
- Monthly global 0.5x0.5 pseudostress fields
  http://www.coaps.fsu.edu/scatterometry/Qscat/gcv_glob_L2B_hlfxhlf.html

We have used our gridded surface winds to examine the propagation of the Madden-Julian Oscillation (MJO). The MJO causes very important variability in the tropics, and is usually identified by it's signal in outgoing long wave radiation and in cloud cover. We have shown that there is a very strong signal in the surface winds (Arguez et al. 2005).

The gridded satellite wind fields have been used to examine variability in the southern ITCZ (SITCZ) in the eastern Pacific Ocean. The results show that our gridded fields are capturing the expected variability on scales of approximately 5 days. Averaging on a monthly scale, such as is necessary with the in situ data alone, hides the vast majority of this variability and masks the existence of the SITCZ. The advection of divergence from the north is caused by several considerations: large scale increase in southward winds associated with gap flow, and spatial changes in vertical mixing associated with changes of atmospheric stability on these spatial scales (Jones 2004).

We are now coupling scatterometer wind observations with various NWP fields to construct forcing fields for our Gulf of Mexico ocean model. This atmospheric forcing is coupled with ocea

n model through surface turbulent fluxes calculated with an updated version (Bourassa 2005) of the Bourassa-Vincent-Wood flux model (Bourassa et al. 1999). The new water-wave related physics considered in this model results in more accurate surface turbulent fluxes for wind speeds from 2 to 30 ms^{-1}.

As noted earlier, the FSU2 winds and satellite products are being freely distributed via the web. The data are also available via anonymous ftp (ftp coaps.fsu.edu/pub/wind) and the DODS (http://www.coaps.fsu.edu/RVSMDC/html/dods.shtml). The operational Pacific FSU2 pseudostress fields continue to be used by U. S. government agencies (e.g., NCEP, NOAA/AOML, NASA/JPL) and universities (e.g., Columbia University, New York University, University of California – Los Angeles, University of California – San Diego, University of Maine, University of Hawaii, and FSU). International users include ECMWF, the Royal Netherlands Meteorological Institute, CSIRO (Australia), the National Institute Of Oceanography in

India, and the Shanghai Typhoon Institute. The quick-look Pacific fields are also reproduced on a monthly basis in the Climate Diagnostics Bulletin distributed by NOAA. At present, the FSU winds are periodically provided to NCAR for archival by their Data Support Section.

8. Surface flux fields from surface observations

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PROJECT SUMMARY

As an adjunct to another project on surface flux observations, ((Observations of Air-Sea Fluxes and the Surface of the Ocean – Atlantic and Pacific VOS; P.I. Robert Weller), this project is designed to 1) produce sea-air heat, moisture, and momentum fluxes from marine weather reports using bulk formulae, and 2) assess the usefulness of those flux estimates in representing variability on seasonal to multi-year time scales. The primary source of long records of air-sea fluxes is human-observer ship weather reports via bulk formulae. To assess diurnal variability and to avoid errors from visual observations of sky-cover and wind taken after dark, we are recalculating the short wave flux and the other flux components using only daytime observations. This daytime-based dataset begins in 1950 and is updated through 2004.

FY 2005 PROGRESS

We have analyzed daytime vs. nighttime surface-flux properties, and produced a preliminary version of bulk formulae surface heat flux (short wave, long wave, latent and sensible components) using only daytime, and only nighttime (for long wave, latent and sensible components), observations. These daytime and nighttime flux datasets cover 1950 through 2004. Because other investigators will prefer to apply their own menu of bulk formulae, we are saving the individual variables required to calculate each flux component.

There are substantial differences between daytime and nighttime properties. Sea-Air surface temperature difference is less in daytime than in the nighttime for each month and over most of the ocean basin, as determined from a separate analysis of the global SST-T_{AIR} distribution. Daytime-only cloud cover is greater than is nighttime-only in most months, by about 0.4 oktas or about 5%, over most of the global ocean, including the stratocumulus-dominated northern oceans. It is suspected that this may result from observer bias—nighttime observers report less cloudiness because they can't see the sky well enough. The shortwave flux from daytime-only cloud cover observations is lower than that calculated from nighttime-only Differences of the shortwave flux calculated from daytime-only vs. that from nighttime-only observations are typically –10 to –40 Watt/m^2. Also, daytime wind speeds tend to be higher by about 0.4m/s or about 5%. This tends to introduce a commensurate increase in the loss of heat that would be calculated from daytime-only vs. nighttime-only observations. Together, greater observed daytime cloud cover and higher daytime wind speeds tend to decrease the shortwave heating and increase the latent and sensible heat losses calculated by daytime-only observations—i.e., a tendency for lower net heat flux.

9. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

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PROJECT SUMMARY

The details of spatial and temporal variations in the flux of fresh water between the ocean and atmosphere must be documented in order to understand, model, and predict variability of the oceanic general circulation and air-sea interaction. The spatial and temporal variability of precipitation is both larger and better observed that that of evaporation over the global oceans, and analyses of global oceanic precipitation are the most important requirement for determining the fresh water flux between the ocean and atmosphere. Therefore, quantitative estimates of oceanic precipitation are crucial and must be available when *Building a Sustained Ocean Observing System for Climate* .

To that end, this science team provides to NOAA's Ocean Observing System for Climate state-of-the-art global gridded analyses of precipitation for a range of spatial and temporal scales. These analyses are based on quantitative estimates from satellite data, because in situ precipitation observations over the ocean are extremely sparse. And of those that are available, many are from islands that are often not representative of the open ocean due to local effects on the atmosphere from the islands themselves. The precipitation analyses that are used primarily for this task were developed and are maintained at NOAA's Climate Prediction Center (CPC). The main precipitation analysis that is used for climatological purposes is CMAP (CPC Merged Analysis of Precipitation), which has a spatial resolution of 2.5º lat/lon and is available back to 1979 in pentad and monthly average form. For in-depth, high space and time investigations, analyses from the CMORPH (CPC MORPHing technique) are used. CMORPH offers estimates of precipitation at a spatial resolution of ~8 km (at the equator) with a temporal reolution of 30 minutes, and these analyses are presently available back to December 2002. Both analyses are updated routinely and made available to various communities of interest.

Brief Description of CMAP

The CMAP technique merges in situ rain gauge observations with estimates that are derived from satellite data. This procedure is akin to Reynold's early blending procedure in which satellite data are used to define the shape of the field and in situ observations are used as anchor points. Over the oceans, the "observations" are primarily comprised of satellite-derived estimates of precipitation, although available in situ measurements (the South Pacific atolls, for example) are incorporated into the CMAP analyses. Bias in the oceanic satellite estimates is reduced by adjusting them by the ratio between the satellite estimates and co-located observations over the South Pacific atoll region. Although the adjustment factor is computed regionally, it is applied globally over the oceans.

Brief Description of CMORPH

It is clear that precipitation estimates that are generated from passive microwave information are clearly superior to those from IR data. However, because of physical limitations with present technology, passive microwave radiometers are only deployed on low orbit (mostly polar orbiting) spacecraft and thus spatial and temporal sampling are a major drawback. IR data yield comparatively poor estimates of rainfall but have excellent sampling characteristics since IR sensors are deployed on geostationary satellites and thus global coverage at fine time and space scales (half-hour, ~4 km) is possible. A number of researchers presently blend these data with the goal to tap the strengths of each by using passive microwave estimates when available otherwise estimates are derived from IR data. CMORPH is a high time-space resolution analysis that blends satellite precipitation estimates from various sources in a unique manner. It uses only precipitation derived from passive microwave and uses IR data, in essence, to spatially interpolate or propagate the precipitating features. The underlying notion is that the error when using the IR in this fashion is less than the error when derived rainfall directly from IR data. Verification bears this out as CMORPH consistently performs better than other merged products (http://www.cpc.ncep.noaa.gov/products/janowiak/us_web.shtml) The technique also provides "radar-like" precipitation estimates over oceanic regions (Figure 1).

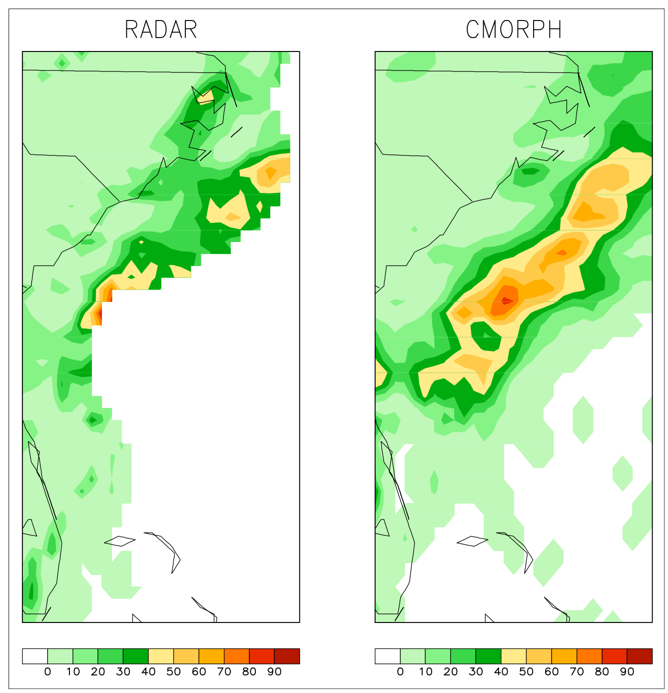

Fig 1. Rainfall estimates from radar (left) and CMORPH (right) for the 24 hour period 12Z June 29 – 12Z June 30, 2005. Units are mm day^{-1}.

In addition to product delivery, this element is tasked with research and development aspects to address known shortcomings in the current analyses. The primary pitfall with the CMAP analyses is the bias correction scheme over the oceanic regions and work has been and will continue to be done to improve this procedure.

The major shortcomings in the CMORPH analyses are 1) the absence of estimates directly from infrared data and 2) the short (presently 3 year) period of record of these observations. The progress on repairs for these problems are reported in the progress report below.

The precipitation analysis systems described above have been developed with the knowledge and support of the GEWEX Global Precipitation Climatology Project and the NASA Global Precipitation Measurement program. As such, the methodology has been vetted through scientist both nationally and internationally. The products were developed and are maintained the Climate Prediction Center and therefore we are highly cognizant of the *Ten Climate Monitoring Principles*. More information about our global precipitation activities, anf the CMAP and CMORPH analyses in particular, is available at http://www.cpc.ncep.noaa.gov/products/global_precip/html/web.html

FY 2005 PROGRESS

CMAP Global Precipitation Analyses

This part of our research project involves two components: 1) documentation of the global oceanic precipitation using the CMAP data sets; and 2) improvements of the current CMAP for better quantitative applications over ocean. In FY2005, we have conducted preliminary research to describe the seasonal and interannual variations of oceanic precipitation and to examine to what extent these variations are reproduced by the NCEP Climate Data Assimilation System (CDAS)-2 which is used to drive the NCEP Global Oceanic Data Assimilation System (GODAS). As shown in Figure 2, large-scale oceanic precipitation patterns, characterized by bands of precipitation associated with ITCZ and storm tracks, are reasonably well reproduced by the CDAS-2. Differences, however, exist in the magnitude of the precipitation and in the latitudinal position of the ITCZ. In particular, the Atlantic ITCZ in the CDAS-2 is about 2.5°-5.0° latitude further south than that in the observation.

In the mean time, we have started to improve the CMAP global precipitation analysis to achieve higher spatial resolution and quantitative accuracy. Originally developed over 10 years ago, the oceanic part of the CMAP global precipitation analysis is defined by com-

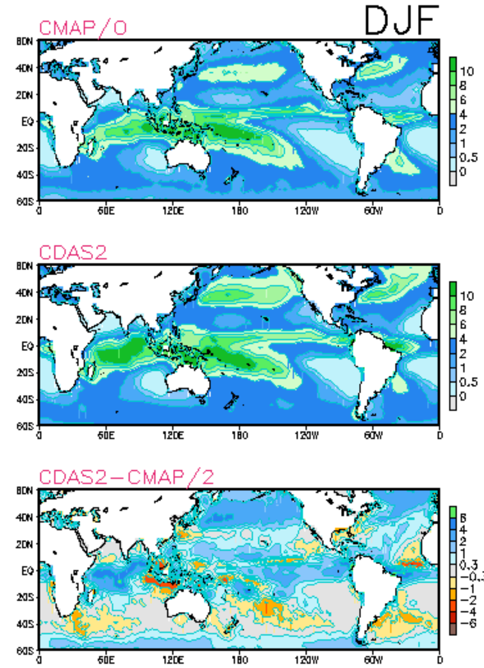

Fig.2 December-January-February (DJF) precipitation (mm/day) averaged over a 25-year period from 1979-2003, from the CMAP global precipitation analysis (top), the NCEP Climate Data Assimilation System -2 (CDAS-2, middle), and the differences between them (bottom).

bining satellite estimates from several different sources to reduce the random error and by combined use of collocated atoll gauge data to reduce the bias inherent in the satellite estimates. Available for an extended period from 1979, the CMAP data sets have been widely used by scientists in atmospheric, oceanic and hydrological communities. Deficiencies, however, exist in the current version of the CMAP analysis. In particular, uncertainties in the magnitude of oceanic precipitation are reported and the grid size of 2.5°lat/lon is not fine enough to resolve the circulation and physical processes that scientists are examining in recent years. With the availability of precipitation estimates derived from newly launched platforms (e.g. TRMM, AMSR and AMSU) and in-situ observations collected from TAO buoys and several field experiments (e.g. EPIC), it becomes possible to refine the CMAP global precipitation analysis for better quantitative accuracy and finer spatial resolution. To this end, in FY 2005, we started to collect and examine the individual precipitation data sets based on in-situ observations and satellite estimates. Fig.3 shows an example of a comparison of three sets of SSM/I-based precipitation estimates with EPIC buoy observations over the tropical eastern Pacific. All satellite estimates examined detected the temporal variations of oceanic precipitation very well, while a bias of about 10-15% is observed compared to the buoy data.

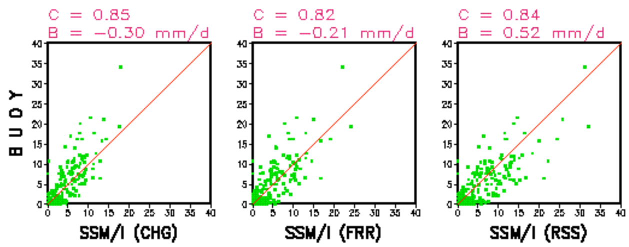

Fig. 3   Scatters plots between EPIC buoy observations over the eastern Pacific and SSM/I-based precipitation estimates produced by NASA/GSFC (left), NOAA/NESDIS (middle), and the Remote Sensing System, Inc. (right). Correlation (C) and bias (B) for each of the SSM/I products are plotted above the scatter plots.

CMORPH Global Precipitation Analyses

In the original CMORPH scheme, only precipitation that is derived from passive microwave instrumentation is used, and infrared (IR) data are used exclusively as a vehicle to move those precipitation estimates in time and to morph them. However, CMORPH will not detect precipitation for instances when precipitation develops and dissipates between microwave observations. Therefore, we developed an algorithm that estimates precipitation directly from IR data. Furthermore, we developed a decision model that determines when to use these estimates. This decision model uses statistics based on the recent performance of the IR-derived estimates and morphed estimates. Much work was completed to fix known deficiencies in the CMORPH methodology prior to reprocessing the record and extending it back in time. A large effort was expended on developing a normalization procedure so that the precipitation products – which are generated from four separate passive microwave instruments (AMSU-B, SSM/I, TMI, AMSR-E), several different estimation algorithms, and eight different spacecraft – blend seamlessly and that their statistical properties (rain rate distribution, etc.) have similar characteristics. Using the support offered by the Ocean Observations program, we have recently hired a person that will assist our efforts in retrieving the needed orbital precipitation products that are necessary to extend CMORPH back in time. We are in the initial stages of this process.

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10. Preparation of Ocean Heat and Freshwater Content Variability Estimates

Sydney Levitus

NOAA/National Ocean Data Center, Silver Spring, MD

PROJECT SUMMARY

Overview and rationale

Rossby (1959) suggested that the world ocean may be the dominant component of the earth's heat balance on interannual-to-decadal- time scales. Recent work (Levitus et al. 2000, 2001,2005) has shown Rossby to be correct. During 1955-98 the world ocean warmed and accounted for more than 80% of the possible increase in the earth system's heat content. The heat content of the world is now recognized as being a critical variable to describe the earth's climate system. Increasing greenhouse gases will result in an increase of the heat content of the earth system with most of the warming occurring in the world ocean.

The NODC Ocean Climate Laboratory (OCL) has provided international leadership in the development of ocean profile databases to provide the data used to make the first estimates of ocean heat content during the 1955-present period. Sydney Levitus is Leader of the IOC Global Oceanographic Data Archaeology and Rescue project (Levitus *et al.*, 2004a). This project has resulted in a doubling of historical ocean temperature profiles for the pre-1991 period. Our work is exemplary of the bullet in the *Summary of user recommendation for observing system enhancements from the 2004 Annual System Review* which is "Build the ocean profile database necessary to compute ocean heat content."

We have previously published the first global estimate of ocean heat content (Levitus et al., 2000; 2001; 2005) for the 1955-98 period for the upper 3000 m of the world ocean. This work attracted considerable attention from the scientific community, Congress, and the media. Figure S1 is an example of our newest work and shows the time series of ocean content for the (0-300 m, 0-700 m, and 0-3000 m layers) the world ocean and individual ocean basins with confidence intervals).

Our work has been used in published IPCC Assessments and will be used in the IPCC 2007 Assessment.

Our work has also been used in an NRC Report to President Bush.

Addressing NOAA's Program Plan

The completed "Ocean Observing System for Climate" as described at the OAR website states that when completed, this system will deliver "for the global ocean, weekly analyses of upper ocean temperature and salinity, sea surface temperature, and sea level." This proposal is a clear start to producing routine upper ocean temperature and salinity analyses.

Management in cooperation with international implementation panels

The P.I. of this project is director of the World Data Center for Oceanography-Silver Spring. He is an advisor to several international data management projects.

Responsible institutions

The Ocean Climate Laboratory of NODC is the Responsible Institution for this project.

Interagency and international partnerships

The P.I. of this project is director of the World Data Center for Oceanography-Silver Spring. He is an advisor to several international data management projects. The P.I. leads the "Global oceanographic Data Archaeology and Rescue (GODAR) Project for the IOC (Intergovernmental Oceanographic Commission) which has the goal of building the most comprehensive ocean profile databases possible through location and rescue of historical ocean profile data. The P.I.s and his colleagues have co-authored scientific publications with colleagues from many different institutions. All scientific results are made available via the World Wide Web.

FY2005 PROGRESS

Measurements and data

During the past four years approximately 900,000 historical and modern temperature profiles have been acquired as a result of funding for other projects. These will be released as part of "*World Ocean Database 2005"*

Analysis and research highlights

Six papers have been published during the past year relevant to this project.

Highlights are:

a. The world ocean continues to warm at a rate consistent with that expected from the observed increase in greenhouse gases in earth's atmosphere since the Industrial Revolution.

b. Gyre and basin-scale variability of salinity is observed in al major ocean basins.

c. The western Mediterranean Sea exhibits changes in ocean heat content that are very similar to the changes in the North Atlantic Ocean.

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11. Development of Global Heat and Freshwater Anomaly Analyses

Gregory C. Johnson[1], John M. Lyman[1,2], Josh K. Willis[3]
[1]NOAA/Pacific Marine Environmental Laboratory, Seattle, WA
[2]University of Hawaii/Joint Institute for Marine and Atmospheric Research, Honolulu, HI
[3]Jet Propulsion Laboratory, Pasadena, CA

PROJECT SUMMARY

Understanding global climate variability requires knowledge of both global heat and fresh water content. Accurate estimates of changes in distribution of heat and fresh water content combined with an analysis of how thermohaline anomalies enter, circulate within, and leave the ocean is necessary to monitor and understand interannual to decadal changes in climate. Such fields and analyses help to verify climate models and improve their predictive skill.

To analyze the structure of global heat content from the existing array of ocean observations, Willis et al. (2004) used a quality-controlled compilation of in situ temperature data from XBTs, CTDs, profiling floats, moored buoys, and autonomous pinniped bathythermographs to estimate global heat content, subsurface temperature, and thermosteric expansion. By including local regressions of altimetric sea surface height (SSH) in the analyses, these estimates are improved and extensions of the estimates are possible in areas where the density of in situ observations is small.

We have updated the estimates of Willis et al. (2004) through 2004. We are working to determine improved error estimates that will allow assessment of the accuracy of the observing array for heat content estimates as the array evolves. We plan to analyze seasonal heat content anomalies and ocean freshwater anomaly estimates in the future.

This project, providing analyses of ocean data, will help NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. To coordinate our analysis activities we participate in regular conference calls of the NOAA Office of Climate Observations Ocean Observing System Team of Experts. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory, but in very close consultation with the co-investigator at NASA's Jet Propulsion Laboratory. The analyses conducted for this project are made in accordance with the ten climate monitoring principles.

FY 2005 PROGRESS

We have updated the satellite altimeter database through the first week of 2005 (the last date for which the merged satellite altimeter sea surface height anomaly fields are available from AVISO). We have downloaded the in situ ocean temperature data through the first quarter of 2005, and then quality controlled those data. We have merged the in situ ocean temperature data and satellite sea surface height anomalies following the procedures of Willis et al. (2004). Following these two steps, we have prepared the heat content anomaly fields for 1993 through 2004. Note that the availability of gridded merged satellite sea surface height anomalies is presently the limiting step for the analysis. These grids are presently available with about a 9-month delay.

Comparing the in situ data distribution for 2004 vs. 1994 (Figure 1 top panel) shows the effect of the growing Argo array, with about twice the number of data for 2004 compared with 1994, and a much more even geographical (and temporal) coverage in 2004 compared with 1994. Since the start of the Argo Program in 2000, the number of in situ observations has steadily ramped up (Figure 1 bottom panel). When the Argo array is at full strength, it alone should deliver about 100,000 temperature profiles per year.

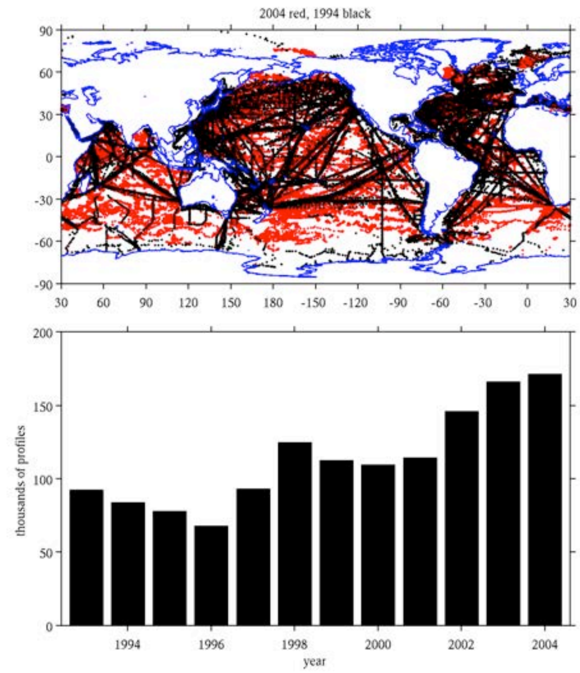

Figure 1. Location of in situ temperature profiles from 2004 (red dots) with 1994 profile locations (black dots) overlaid (top panel). Number of in situ temperature profiles (bottom panel).

The difference between 2003 and 2002 heat storage (Figure 2, top panel) and that between 2004 and 2003 (Figure 2, bottom panel) demonstrate the large year-to-year variability in ocean heat storage, with changes reaching or exceeding the equivalent of a 80 W m^{-2} magnitude surface flux over a year in many places. Ocean advection likely plays a large role in many of these changes. For instance, the shift from El Nino conditions in 2002 to more neutral conditions in 2003 can be seen in the negative values along the equator in the top panel of Figure 2. The large changes in both years associated with the western boundary currents and the Antarctic Circumpolar Current are likely partially due to advection as well.

Linear trends in heat storage estimated over the entire 12-year record (Figure 3, top panel) generally have larger spatial scales but smaller amplitudes than the year-to-year changes. Examination of the ratio of the

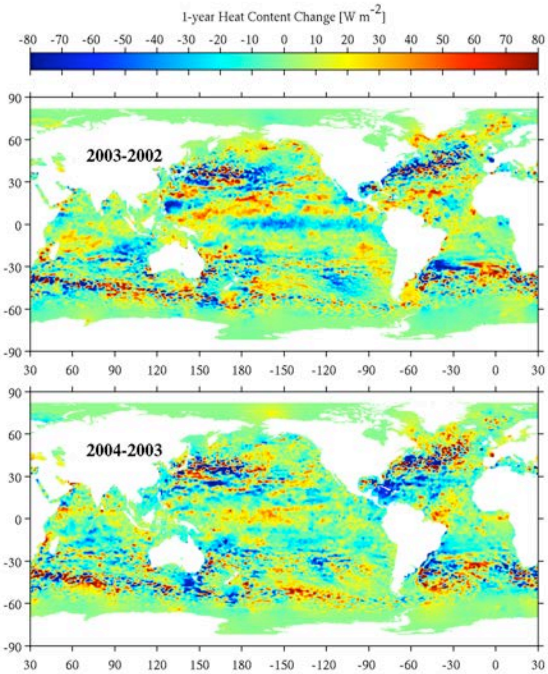

Figure 2. Heat Storage changes for the 1-year average for 2003 with that for 2002 subtracted (top panel) and for the 2004 average with that for 2003 subtracted (bottom panel).

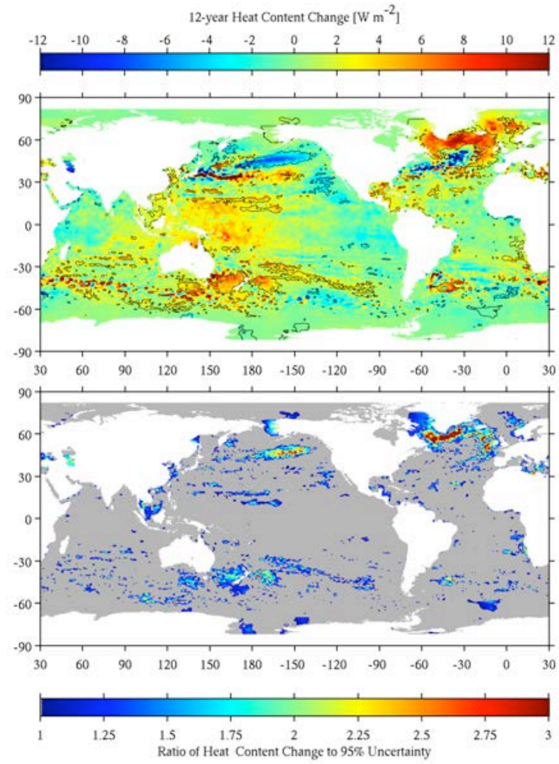

Figure 3. Linear estimates of heat content change from 1993 to 2004 (top panel) with areas of significant slope outlined in black as estimated by the ratio of these trends to their 95% uncertainty estimates (bottom panel, where colored regions are significantly different from zero but grey are not).

trend to the 95% uncertainty in the trend (Figure 3, bottom panel) shows that the trend is significant only in limited regions. The large positive values in the northern North Atlantic Ocean may be due in part to the mid 1990's shift in the North Atlantic Oscillation. The large negative values in the subpolar North Pacific may partly reflect changes in the Pacific Decadal Oscillation. The Southwest Pacific also contains significant positive values, including south of Australia, in the Tasman Sea, and east of New Zealand.

Although linear trends over the 12-year record (Figure 3, top panel) have only a few significant regional patterns (Figure 3, bottom panel colored regions) that reflect the influences of decadal ocean variability, globally integrated heat content (Figure 4) shows a smaller, steadier, more significant trend, 0.91 (±0.15) W m^{-2}. There is a slight (although not statistically significant) reduction in ocean heat storage at the end of the time-series. This reversal occurs between 2003 and 2004, after the 2002 El Niño. Interestingly, the other slight reversal in ocean heat gain in the time series occurs between 1998 and 1999, after the 1997 El Niño.

The error bars on the globally averaged heat storage follow Willis et al. (2004) by including three contributions. In that paper a random contribution (0.6×10^7 J m^{-2}) accounts for the RMS error in globally averaged sea level about a 1-year mean. A second systematic contribution (1.1×10^7 J m^{-2}) accounts for potential slow drift in the altimeter measurements. A third random contribution accounts for undersampling of the global mean by the in situ data. Like the other two errors, Willis et al. (2004) estimated this last random error (1.3×10^7 J m^{-2}) as an average one for the entire time-series.

However, we are interested in how the evolving observational array modifies the error bars on our estimates of ocean heat storage variability from year to year. To quantify the effect of improved in situ ocean heat content measurements over time as the Argo array grows, we interpolated each year (from 1993 through

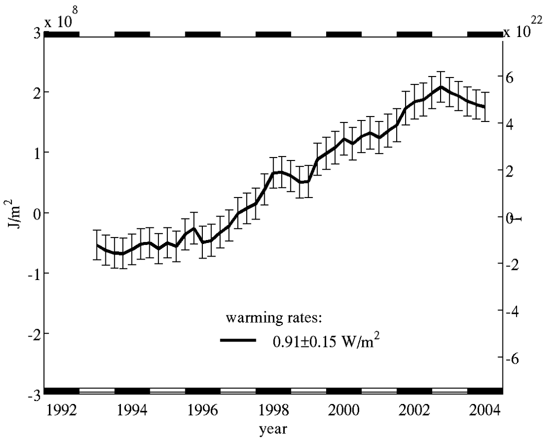

Figure 4. Globally averaged interannual heat content anomalies (solid line) based on the Willis et al. (2004) methodology. Error bars show 95% confidence limits. The linear trend with 95% confidence limits is given.

2004) of synthetic heat anomalies generated from the altimeter data following Willis et al., (2004) to the locations and time of year of in situ observation locations for a given year. We then used these interpolated values as fake "in situ" data to construct heat anomaly maps using the Willis et al. (2004) methodology from 1993 through 2004 and a given year's sampling pattern. For a given year's sampling pattern, we then compared each of the 12 mapped fields to the fully resolved synthetic fields. This yielded a variance from which the error estimate was derived. This contribution to the error bars in Figure 4 can be seen to vary significantly from year to year (Figure 5).

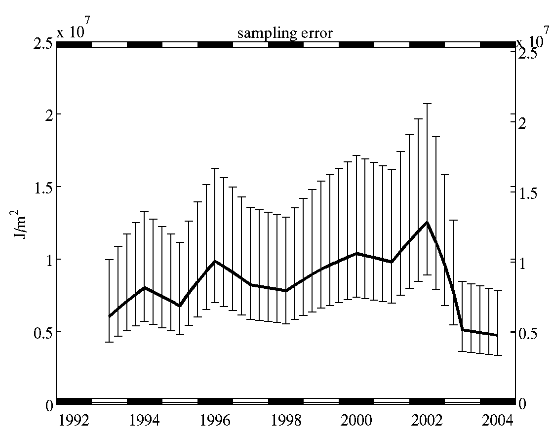

Figure 5. Global heat content mapping error due to undersampling of the global mean by the in situ data, with 95% confidence limits.

Most notably, as the Argo array grew dramatically in 2003 and 2004 with more widespread sampling than previous years (see. Figure 1), this contribution to the error bars was reduced by more than a factor of two compared with the previous few years (Figure 5). There may still be a lag of several years for in situ data to makes its way to the archives we are using, in which case error bars for subsequent analyses that include additional in situ data will be further reduced.

In reality, magnitudes of all three error contributions should be reduced by improved sampling, since altimeter RMS noise and any false trends in the altimeter data should also be reduced by the presence of more and better distributed in situ data. We are working on the correct methodology to make all components of our error bars time-dependent to reflect year-to-year changes in the ocean observing system array sampling. When we have estimated error bars which take all aspects of interannual sampling variations into account, we will prepare a manuscript on the results outlined above for publication.

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12. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage.

Claudia Schmid and Gustavo Goni
NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

The main objective of this project is to provide quarterly reports that evaluate the accuracy of estimates of the global upper ocean heat storage and its time derivative. This product will show (a) locations where upper ocean temperatures were collected in each quarter, (b) how well the observations satisfy the GOOS/GCOS temperature requirements, (c) the locations where future observations are needed to improve the observing system, and (d) how successfully the system reduces the potential bias error. This product will display the performance in terms of these goals since January 1997 and will be used to detect anomalies of the heat storage. The evaluation will incorporate profiles of temperature and salinity from XBTs, CTDs and Argo floats. In addition these estimates will be compared with heat storage estimates from altimetry. The heat storage estimates from altimetry will also be used to extend the heat storage fields into regions where the coverage with in-situ data is poor. An example for the expected quarterly product is given in Figure 1.

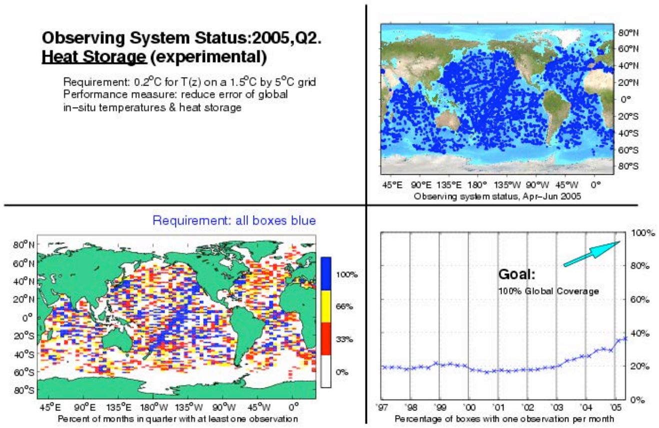

Figure 1: Preliminary example of Quarterly System Status Report for Upper Ocean heat storage, covering the time period April through June 2005. The goal of this additional task is to generate quarterly reports for the global ocean.

Project description:

Profiles from XBT, CTD and profiling floats, and data from profiling floats are part of the Global Ocean Observing system. The increasing number of profiles makes an improved estimation of the upper ocean heat storage possible. This parameter is critical for the understanding of the climate system and it has been shown to have a significant impact on the weather over adjacent landmasses and on the strength and frequency of tropical cyclones. Therefore, improving the accuracy of estimates of the upper ocean heat storage and budget is key for climate research.

In this work we estimate the heat storage of the upper ocean on a quarterly basis on a regular grid, both for the mixed layer and for layers of constant depths. To accomplish this, upper ocean temperatures from various sources and instruments (WOD 2001, GTSPP, Argo, XBTs, including high-density lines; thermistor chains; profiling floats; CTDs) are being combined.

All profiles undergo a series of quality control tests to ensure that only profiles of good quality are used in the analysis. For Argo floats these tests are described in a document available on the Internet (http://www.ifremer.fr/coriolis/cdc/argo_rfc.htm - link to ``Argo Real-time Quality Control Tests Procedures''). Similar tests are applied to all non-float profiles. Additionally, quality control tests are performed to detect profiles that deviate significantly (by 10 standard deviations or more) from the NCEP reanalysis and the World Ocean Atlas 2001 or from other profiles collected in the same region and time period. Failing profiles are reviewed by an operator to determine if they are good, bad or correctable. Preparatory work was performed in the Atlantic to ensure that XBT and float profiles can be combined without introduction of artificial climate signals.

The currently available upper ocean data set covers the period 1968 to present. The data will be analyzed on a year-by-year basis. For the purpose of this proposal, the quarterly heat storage is being derived for 1997 to present. Once the system is operational an extension into earlier years will also be attempted.

Additionally, we are conducting comparisons between altimetry- and hydrographic-derived estimates of upper ocean heat storage, which will allow us to investigate the extent in depth of the sea height signal in different regions of all ocean basins. The local changes in upper ocean heat storage are estimated from altimetry-derived sea height anomaly fields, using regressions based on historical observations. For example, similar estimates are currently used to clearly identify long periodic climate signals, such as the variability of the warm pool in the western Pacific Ocean associated with El Nino.

Of key interest are the dynamical effects that have been shown to be dominant over steric effects in some regions, where a very weak sea surface signal is observed as a compensation of these two components. Altimetry observations will also allow us to complete our estimates in regions where hydrographic data are not available or severely under-sampled in space and time.

Responsible Institutions:

NOAA/AOML is solely responsible for managing all aspects of this project.

FY 2005 PROGRESS

Details of the Quarterly Reports:

We started creating the Quarterly Status Report for the upper ocean heat storage on a quarterly basis. Development of a methodology to establish the accuracy of the heat storage based on the error estimates of the in-situ temperature (T(z)) for which the requirement is 0.2˚C. This product will be used as guidance for the future collection of hydrographic data. It will also achieve the objective required by OCO to identify the locations where anomalies occurred. It is anticipated that the quality of the heat storage estimates from satellite altimetry will depend on the region. This could help to optimize the in-situ observation system by increasing the number of collected profiles in regions where the satellite-derived estimates are less reliable.

Research Highlights:

- Develop software to produce global quarterly fields of the heat storage from in-situ observations.
- Develop software to produce global quarterly fields of the heat storage from satellite altimetry.
- Comparison of the two independent estimates of the heat storage
- Produce status reports (without potential bias, Figure 1)
- In progress: Identification of regions where satellite estimates can supplement the estimates from in-situ observations (Figure 2).

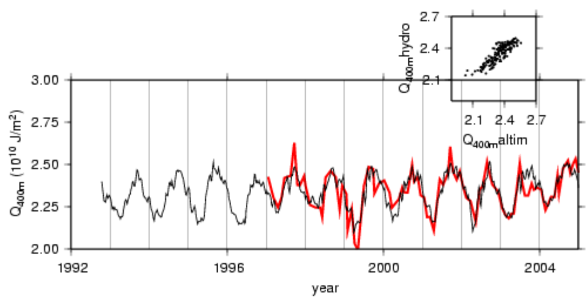

Figure 2. Time series of heat storage from the surface to 400m deep in an area of the tropical Atlantic (5°x1.5° box centered in 27.5°W and 5.25°N) as estimated by profiling floats (red) and by altimetry (black). The regression coefficient is 0.9 and the rms difference is 0.04$10^{10}$J/m^2.

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13. Evaluating the Ocean Observing System: Surface Currents

Rick Lumpkin and Gustavo Goni
NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

Goal

Evaluate surface current observations collected by the Global Climate Observing System. This product will demonstrate: (a) where surface current observations were collected in the most recent quarter, (b) how well the system has satisfied the GOOS/GCOS requirement for surface currents (2 cm/s accuracy, one sample per month at 600 km resolution), (c) where future drifter deployments are needed to improve the observing system, and (d) how successfully the system has reduced the potential bias error (cm/s) in satellite-based surface current calculations. This product will display since 1998 the performance in terms of these goals, allowing the observing system's evolution to be evaluated. The product will incorporate drifting buoy, satellite altimetry, wind and moored current observations.

Project Output

Quarterly reports to evaluate surface current measurements collected by the Global Ocean Observing System.

Overview

The Global Ocean Observing System (GOOS) measures many processes and parameters relevant to climate variability. Of relevance to this project, GOOS measures ocean surface currents, necessary to quantify ocean advection of properties such as heat. Interannual variations of heat advection are a well-known component of ENSO variability, and may also play a significant role in tropical and North Atlantic variations (and related climate impacts in the Americas, Europe and Africa).

This project aims to evaluate how well the GOOS has met the requirement for near-surface current observation stated in the GOOS/GCOS (1999) document. This requirement is: 2 cm/s accuracy, one sample per month at a resolution of 600 km. We interpret the accuracy requirement as demanding observations from either a moored current meter (typically an acoustic-based point measurement within the upper 20m) or from a drogued Surface Velocity Program-type drifter. Drifter observations are quality controlled and distributed by the drifting buoy Data Assembly Center at NOAA/AOML; current meter observations are quality controlled and distributed by the TAO Project Office at NOAA/PMEL.

Our evaluation of GOOS surface current observations is done on a quarterly basis. The first experimental quarterly report, for Q2, 2005, appears as Fig. 1. The observing network of drifting and moored buoys is shown in the upper-right panel of the quarterly report. We divide the ocean into 5.39º (600 km at the equator) boxes,

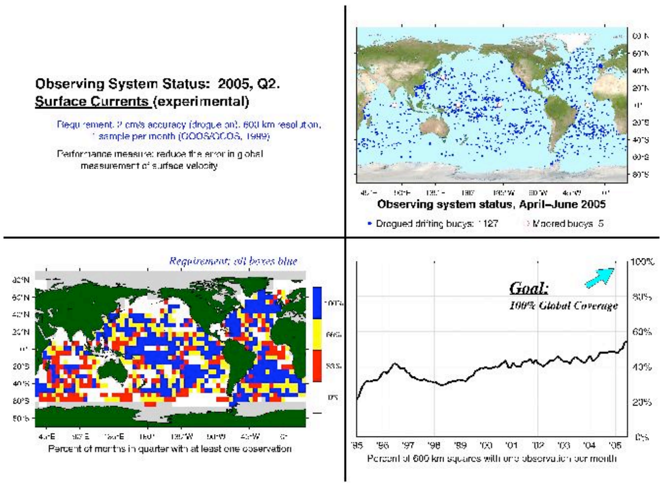

Figure 1: Report for the second quarter (April-June) of 2005 for Surface Currents. The Global Ocean Observing System has reached 55% of its goal of measuring near-surface currents at the resolution specified in the GOOS/GCOS document.

and for each month we count the number of observations within each box. A single observation by a drogued drifter or moored current meter is considered to meet the GOOS/GCOS requirement. If a box was sampled at least once in all three months of the quarter, it is colored blue (100%) in the lower-left panel. If it was sampled for two of the three months, it is yellow (66%); one of the three months, red (33%); none of the three months, white (0%). Grey boxes are ice-covered, average less than 20m in depth, or are mostly occupied by land. A time series of the overall success rate is shown in the lower-right panel: if 50% of the non-grey (or land) boxes were sampled at least once by a drifting or moored buoy in a month, the curve will have the value 50% on that month.

In the future, a plot will be added that quantifies the global bias in currents derived from satellite altimetry and winds, given the distribution of the observing system to correct for spatially varying biases. These biases may be due to errors in the Ekman model or winds, other large ageostrophic terms such as centrifugal forces in strong rings, or surface/subsurface compensating effects that eliminate the sea level anomaly signature of near-surface currents. In the future, operational satellite-based surface current fields will be produced globally from satellite observations, calibrated using the in-situ observations from the Global Ocean Observing System as is done with SST today

Responsible Institutions

NOAA/AOML is solely responsible for managing all aspects of this project. The PIs acknowledge Paul Freitag (NOAA/PMEL) for his input.

FY 2005 PROGRESS

Products Delivered

The first quarterly report was generated for Q2, 2005. The Q3 report is currently being prepared.

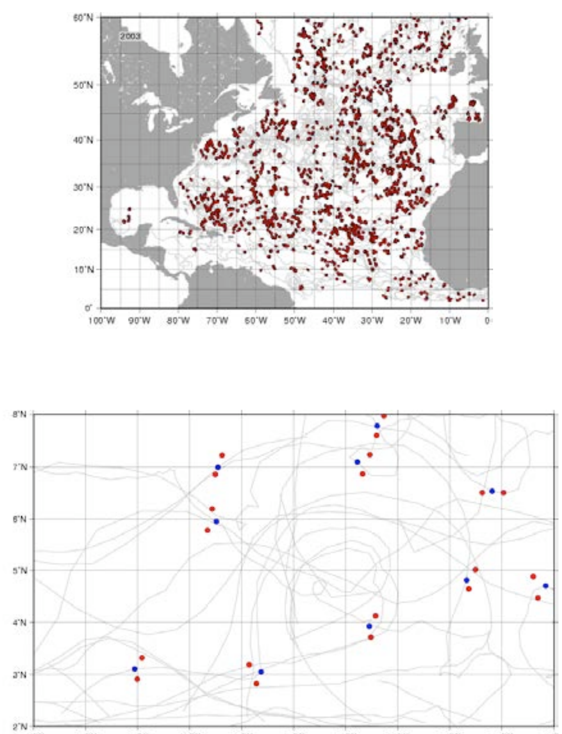

Figure 2: (Top) Locations where altimeter groundtracks cross drifter trajectories on the same day during 2003. (Bottom) Detail showing concurrent locations of drifters (blue) and altimeter sea height anomalies (red).

Scientific Findings

Work has been initiated on the altimetry component of this project. We will be comparing the alongtrack sea height anomaly differences with the drifter-derived velocities where an altimeter groundtrack crosses a drifter trajectory on the same day. Matches for a given year are shown in Figure 2. Initial estimates of the directly wind-driven (Ekman) motion have been made from NCEP/NCAR Reanalysis winds; future efforts will include scatterometer-based winds from e.g., QuikSCAT.

Progress Highlights:

- Collection of data necessary to generate Quarterly Report. This includes surface drifter data and near-surface current observations from moored buoys.
- Preliminary Status reports starting in Q2, 2005.
- Status report distributed for dissemination through the AOML State of the Ocean web pages and at the Office of Global Programs web site.
- Comparison of altimetry, winds and drifter observations initiated.

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14. Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean.

Molly Baringer, Silvia Garzoli, Gustavo Goni, Carlisle Thacker and Rick Lumpkin

NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

Goal

To contribute to the assessment of the state of the ocean by providing quarterly reports on the meridional heat transport in the Atlantic Ocean. This heat transport is directly related to the role that this basin plays in the meridional overturning circulation (MOC) and is an important benchmark for integrated air-sea fluxes and numerical model performance.

Project Output

"State of the ocean" quarterly estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic. This project funds the development of a methodology to estimate heat transport variability using data collected along two high density XBT lines operated by AOML, satellite data (altimeter and scatterometer), wind products from the NCEP reanalysis and products from general circulation models. Quarterly reports are posted on the AOML web site.

General Overview

The Atlantic Ocean is the major ocean basin involved in large-scale northward transports of heat typically associated with the meridional overturning circulation (MOC) where warm upper layer water flows northwards, and is compensated for by southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the entire Atlantic Ocean. Historical estimates of the net northward heat flux in the vicinity of its maximum, which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[7] to 1.6 PW, while estimate in the 30°S to 35°S band are even more uncertain, ranging from negative to more than 1 PW. While much of this variability may be a consequence of the different methods used to estimate the heat transport, natural variability cannot be ruled out. The importance of this heat transport to the world climate together with the possibility of monitoring its variability motivates this project.

AOML collects XBT data on two lines spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along AX7 running between Spain and Miami, Florida and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along AX18 between Cape Town, South Africa and Buenos Aires, Argentina. These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data can also be usefully augmented with other data from the NOAA/OCO funded Florida Current transport program.

Heat transports have already been successfully computed using XBT data (Roemmich et al, 2001), however the methodology for estimating the transport can be improved. In particular, as density is essential for the flux estimates, results depend on how well salinity profiles can be estimated to complement the XBT data and on how well the profiles can be extended to the bottom

[7] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports.

of the ocean. Improving these estimates to achieve more accurate fluxes is an essential part of this project, as is a careful quantitative assessment of the accuracy of the resulting fluxes.

Methodology

Northward mass, volume, and heat transport through a vertical plane

$$M = \iint \rho v \, dxdz \quad [\text{Kg/s}] \qquad V = \iint v \, dxdz \quad [Sv = 10^6 m^3/s] \qquad H = \iint \rho c_p \theta v \, dxdz \quad [PW = 10^{15} Watts]$$

can be estimated directly from observations. The northward velocity *v* can be treated as a sum of three terms: (i) a geostrophic contribution (thermal wind equation) relative to a prescribed reference level, (ii) an ageostrophic part modeled as Ekman flow, and (iii) a barotropic part define as the velocity at the reference level. Density ρ can be obtained from XBT data if salinity is accurately estimated and data are extrapolated to the ocean bottom.

Preliminary estimates of mass and heat transport have been obtained from temperature profiles collected along AX07 and AX18 high-density lines using Sippican T-7 XBT probes, which typically provide data to 800 m or deeper. Salinity was estimated for each profile by linearly interpolating the closest of Levitus' climatological mean salinity and temperature profiles to the XBT temperature and the climatological profiles were used to extend the data to the bottom. In computing geostrophic velocities, a reference level, based on previous work in the literature and on what is known about the circulation, was prescribed just below the northward flowing Antarctic Intermediate Water (σ_0=27.6 kg m^{-3} in the North Atlantic and σ_0=27.4 kg m^{-3} in the South Atlantic). Within strong flows such as the Florida Current or the Malvinas Current where no level of "no motion" can be found, the transport must be specified (e.g. by the mean value of the Florida Current, etc.). The velocity at the reference level is adjusted so that the net mass transport across the section is zero using a single velocity correction for each section. Typically, values of this correction ranged from 10^{-4} to 10^{-6} m s^{-1}.

Responsible Institutions

NOAA/AOML is solely responsible for managing all aspects of this project. .

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Products Delivered

Quarterly reports were designed that show the estimated heat transport for each high density XBT section along the AX7 and AX18 lines (Figure 1 and 2). The value of heat transport for that section is listed along with the station positions for the cruise and the temperature obtained from the XBTs. The current heat transport estimate is shown in context with previous estimates in graphs of all heat transport values through time and of heat transport values as a function of time of year. Values of heat transport vary from 0.5 to 1.6 PW for each of the sections (1 PW = 10^{15}W). One PW is equivalent to the amount of energy produced by about one million nuclear power plants.

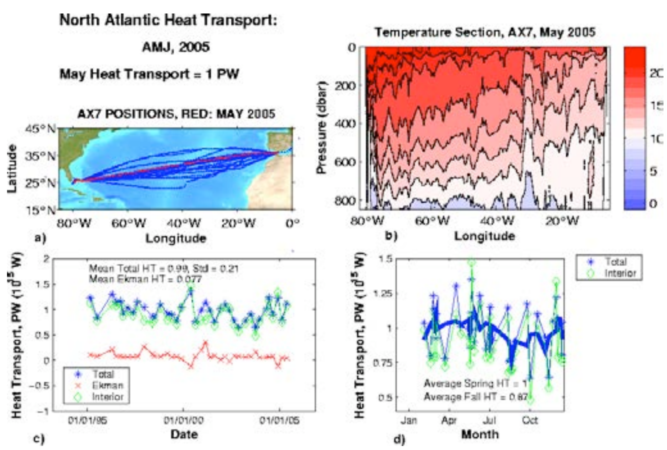

Figure 1: Report for the second quarter (April-May-June) of 2005 for North Atlantic Meridional Heat transport along the AX7 high density XBT line. Transport results based on May 2005 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left). Heat transports demonstrate a small seasonal signal (lower right) with spring sections having a higher heat transport than fall sections.

Scientific Findings

In the North Atlantic, the heat transport was found to vary on inter-annual time scales from 0.8 ± 0.2 PW at present to 1.2 ± 0.2 PW in 1996 with instantaneous estimates ranging from 0.6 to 1.6 PW (Figure 1). Heat transport due to Ekman layer flow computed from annual Hellerman winds was relatively small (only 0.1

PW). This variability is entirely driven by changes in the interior density field; the barotropic Florida Current transport was kept fixed (32 Sv[8]). Improvements to these estimates should include (i) time varying Florida Current transports and wind fields, (ii) improved salinity estimates and extrapolations to the bottom, and (iii) improved error estimates that reflect the effect of the initial reference level, the wind field variability, the importance of barotropic flows, and the uncertainties of the salinity estimates and the extrapolations

During preliminary tests assessing the validity of the methodology in the South Atlantic, several of these error issues were considered more closely. Simulated data from a general circulation model indicated that obtaining heat transport using a level of no motion instead of the total velocity results in a bias error. At 30°S (35°S), the heat transport calculated from the velocity field was 0.55 PW (0.51 PW), the heat transport calculated from T and S was 0.85 PW (0.80 PW), and the heat transport calculated from T and S adjusted by a bottom velocity at the boundary provided by the literature was 0.60 PW (0.50 PW). The conclusion was that the transports must be adjusted for a barotropic component in the Malvinas Current region and that the "level of no motion" assumption does not hold near strong western boundary currents. Note that in the North Atlantic a good estimate for the barotropic western boundary current is readily available. Current meter moorings deployed by French scientists in the Malvinas Current will provide these values for the South Atlantic. Data collected along the A10 WOCE line located near 30°S were used to estimate the errors induced by using a climatological deep T, S field from the Levitus product instead of actual data. Results indicated that this procedure can introduce an error of up to 25% and that in order to reduce the errors a better climatology and better T/S relation is needed. Additional results indicate that the use of different wind products to calculate the Ekman component of the flow induced an error of 10%. Particularly in the South Atlantic, the Ekman transport estimates vary with latitude and season. One of the main challenges to providing an accurate heat transport is the lack of accurate information on the South Atlantic boundary currents.

Progress Highlights

Progress highlights to date include:

- Collection of data necessary to generate Quarterly Report.
- Preliminary Status reports starting in May 2005.

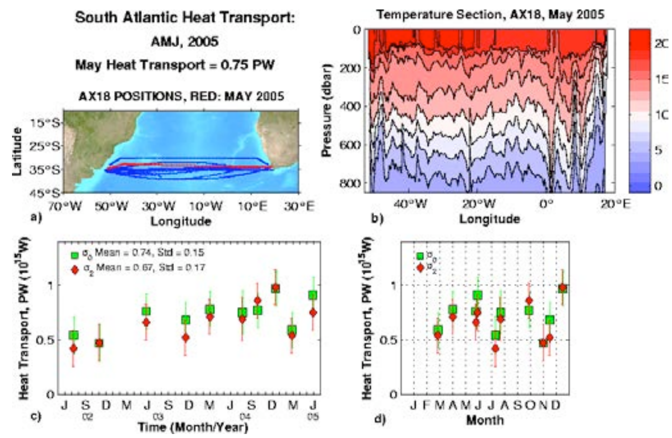

Figure 2: Report for the second quarter (April-May-June) of 2005 for South Atlantic Meridional Heat transport along the AX18 high density XBT line. Transport results based on May 2005 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Heat transports demonstrate no significant seasonal signal (lower right).

- Construction of State of the Ocean web page completed that will disseminate all quarterly reports funded by NOAA/OCO.
- Status report distributed for dissemination through the AOML State of the Ocean web pages.
- Improved Salinity estimation algorithm initiated.
- Improved subsurface climatology initiated.
- Improved estimates of boundary current transports using satellite altimetry initiated.

Research Highlights

1. AOML has developed this Quarterly report on the "state of the ocean" using XBT data to estimate heat transport from two of its high-density lines. These reports are summaries of ongoing research and are a means to present to managers and decision makers summary information on the state of the ocean, in this case the intensity of the heat transported by the meridional overturning circulation. Heat transport variability is an important indicator of climate variability since the poleward oceanic temperature heats the atmosphere. The quarterly reports will indicate the amount of heat transport in the North and South Atlantic and how anomalous the values are.
2. Estimates of the meridional temperature transport have been obtained for the South Atlantic that

[8] Sv is a Sverdrup or 10^6 m^3/s, a unit commonly used for ocean volume transports.

suggest the northward transport is larger than previously reported (0.7 PW instead of the 0.4 PW reported previously). Little is known about the certainty and variability of temperature transport in the South Atlantic due to the paucity of observations there. These estimates represent the first measure of the variability in the South Atlantic. The South Atlantic region is particularly important because it is where the upper limb of meridional overturning circulation is blended together from sources from the Indian and Pacific Ocean. The relative influence of the Indian and Pacific Oceans is important for long-term climate prediction.

3. Preliminary estimates of the temperature transport in the North Atlantic suggest a reduction in the transport over the previous 10 years from values near 1.2 PW to values near 0.8 PW. A reduction in northward temperature transport of up to 30% over a ten-year period could have substantial impacts on climate. Continued monitoring and refinement of the temperature transport is the focus of a large international program funded to monitor the strength of the total meridional overturning circulation (MOC) volume and heat transport at mid- latitudes in the North Atlantic to monitor for rapid climate change signals. These new XBT derived estimates if validated against the more complete observations funded in the international program, could help provide one component of a less expensive long-term monitoring system used to predict climate change.

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15. Management of NOAA's Carbon Monitoring Network

Project 1: CLIVAR/ CO_2 Repeat Hydrography Program CO_2 Synthesis Science Team

Richard A. Feely[1], Rik Wanninkhof[2], Christopher L. Sabine[1], Tsung-Hung Peng[2], Robert Key[3], Frank Millero[4], Andrew Dickson[5], and Alex Kozyr[6]

Project 2: An End-to-end Data Management System for Ocean pCO_2 Measurements

Steven C. Hankin[1], Richard Feely[1], Alex Kozyr[6], and Tsung-Hung Peng[2]

Project 3: Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations

Christopher L. Sabine[1], Richard A. Feely[1], Tsung-Hung Peng[2], Robert Key[3], and Alex Kozyr[6]

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PROJECT SUMMARY

1.1 General Overview

The ocean plays a critical role in the global carbon cycle as it is a vast reservoir of carbon, naturally exchanges carbon with the atmosphere, and consequently takes up a substantial portion of anthropogenically-released carbon from the atmosphere. Although the anthropogenic CO_2 budget for the last two decades, i.e. the 1980s and 1990s, has been investigated in detail (Prentice et al., 2001), the estimates of the oceanic sink were not based on direct measurements of changes in the oceanic inorganic carbon.

Recognizing the need to constrain the oceanic uptake, transport, and storage of anthropogenic CO_2 for the anthropocene and to provide a baseline for future estimates of oceanic CO_2 uptake, two international ocean research programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), jointly conducted a comprehensive survey of inorganic carbon distributions in the global ocean in the 1990s [Wallace, 2001]. After completion of the US field program in 1998, a five year effort – the Global Ocean Data Analysis Project (GLODAP) - was begun to compile and rigorously quality control the US and international data sets including a few pre-WOCE data sets in regions that were data limited (Key et al., 2004). Although these data have improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean, they have yet to be fully exploited to examine the mechanistic controls on these carbon distributions or to understand the temporal patterns of variability.

Most of the approaches used to estimate anthropogenic CO_2 in the oceans are based on assumptions of steady state circulation and constant biology. It is becoming increasingly apparent that these assumptions may not hold in a global change environment. The most important component of an assessment of ocean biogeochemical change, whether of natural or anthropogenic origin, is high-quality observations. The WOCE/JGOFS data set provides an important point of reference for ocean carbon studies. Many other useful data sets have not been analyzed in such a context, however because there has not been a coordinated effort to bring these data together and no data management system to make navigation and exploitation of these data convenient.

The NOAA Office of Climate Observation's Carbon Monitoring Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). It is not sufficient, however, simply to collect and archive the data, if we expect the data to improve our understanding of the global carbon cycle and the role of the ocean in climate change. Recognizing the need for proper data management and synthesis, the OCO has funded several projects to manage and perform an initial interpretation of the data collected from the Carbon Monitoring Network. Because three of these OCO projects are very closely linked and often work together to generate an end product, we have combined the summary of the FY05 progress and FY06 plans for these projects into one report. These projects span the spectrum from coordinated data collection and quality control/quality assessment (Science Team) to the ingestion of data and development of web-based tools for visualizing the data (Data Management System) to synthesis and interpretation (Synthesis Project).

The Science Team is made up of the Repeat Hydrography inorganic CO_2 system PIs (R. Feely-PMEL, C. Sabine-PMEL, R. Wanninkhof-AOML, F. Millero-RSMAS, and A. Dickson-SIO) and investigators with expertise in data synthesis and management (R. Key-Princeton, T-H. Peng-AOML, and A. Kozyr-CDIAC). Among the duties of the Science Team is the responsibility for coordination. The Science Team works very closely with all of the PIs associated with the Carbon Monitoring Network and helps to organize annual PI meetings to discuss issues of coordination. The sequence, timing, and protocols of the repeat hydrography sections must take into consideration the US Carbon Cycle Science Program (CCSP) objectives, and consider the timing of national and international programs. This coordination is conducted through the Science Team. Members of the Carbon Monitoring Network are participating in national and international planning efforts to evaluate and improve the global ocean CO_2 database via the International Ocean Carbon Coordination Project (IOCCP). The Science Team also works with the Network PIs to gather the carbon data, perform the initial QA/QC on the completed data sets and work with the other carbon management projects to merge these data into a single globally consistent data collection and evaluate them utilizing techniques similar to those used for the WOCE/JGOFS synthesis (Sabine *et al*., 2005; Lamb *et al*., 2002; Wanninkhof *et al*., 2003).

The Data Management System project is focused on reliable and efficient data management within the NOAA Global Carbon Cycle Program. This requires standards and infrastructure to: upload/ingest new data; quality control data sets; provide users with timely access to data; and ensure its long-term archival. The October 2001 Carbon Data Management Plan, a product of the carbon data management workshop held at PMEL (Feely and Sabine, 2002), articulates a community consensus on the need for a systematic approach to ocean CO_2 data management. The ultimate objective of the plan is to provide the oceanographic community with easy access to high-quality near real-time CO_2 and related physical, chemical and biological data sets. The plan outlines the need for new standards regarding analytical measurement techniques, data formats, metadata content, quality control, and assessment procedures. The plan recognizes that the data management system must build upon existing capabilities and must be compatible with the emerging standards for integrated ocean data management within the U.S. It identifies the Carbon Dioxide Information Analysis Center (CDIAC) as a regional quality control and data management facility and the Live Access Server (LAS) from PMEL as a sound software foundation for the system. It also recommends the creation of a CO_2 science team and a data management group to guide the creation of standards and the evolution of the data management system.

The Data Management System is a road map for the implementation of that data management plan and a process for governance of that system under the Science

Team. The vision of the data system is of five integrated components coordinated through a suite of data standards and procedures. The components are i) local QA/QC and the initial collation of shipboard data; ii) regional QC and assembly of data and metadata; iii) operational data base management; iv) the Web-based data and metadata access and visualization subsystem; and v) permanent archival. The partners in the development of this solution are S. Hankin-PMEL, R. Feely-PMEL, A. Kozyr-CDIAC and T-H Peng-AOML.

The goal of the Synthesis Project is to lay the groundwork for understanding the impact of climate change on ocean biogeochemistry using past and current observations. A five year data synthesis activity for the WOCE/JGOFS/OACES global carbon data set has just been completed. While the GLODAP climatology provides a critical baseline for the evaluation of post-WOCE cruises, it does not fully utilize the available data that can contribute to an understanding of the temporal evolution of carbon in the ocean. The Synthesis Project is working with the Science Team and Data Management System to develop the next phase of analyses for the modern global carbon data set. We will not only continue to examine the existing GLODAP data, but will also begin developing a temporal component to the data base and analysis program to examine how the ocean carbon cycle is changing over time. In these analyses we will incorporate recent data obtained from the Carbon Monitoring Network including surface pCO_2 observations from ships and buoys and water column data from the CLIVAR/CO_2 Repeat Hydrography Program. We will also incorporate historical and current data from previous national and international efforts. These additional data will include large data collections from the North Atlantic and North Pacific which have recently become available.

The members of the Synthesis Project funded by the OCO are C. Sabine-PMEL, R. Feely-PMEL, T.-H. Peng-AOML, R. Key-Princeton, and A. Kozyr-CDIAC. However, we anticipate working closely with other national and international colleagues in the analysis of these data including the PIs for the NOAA Carbon Monitoring Network that are not represented here and others that are seeking funding from other sources to work with us (e.g. Princeton and NCAR modeling groups).

These three projects work together with the OCO carbon measurement projects to take the fundamental carbon observations and turn them into products that are useful for scientists and the public for understanding the ocean carbon cycle and how it is changing over time. An integral part of this work is our relationship with the Carbon Dioxide Information Analysis Center (CDIAC). Even though CDIAC is one of several world data centers, we have explicitly included them in these projects to ensure a close interaction between our efforts and those of the rest of the community and the public. CDIAC will not only act as the primary repository for the NOAA ocean carbon data, but also provides our link to the international data sets and a well known focal point for disseminating the information obtained through these projects out to the general public. This interaction does not preclude interactions with other world data centers (e.g. NODC), but provides a useful mechanism for distributing our results to these other data centers.

1.3 Addressing NOAA's Program Plan

These projects are the component of the Ocean Carbon Monitoring Network, that makes the ocean carbon measurements relevant and useful to the general public and are identified as key elements of a network design in the Program Plan. In particular, these projects help ensure that the network is following items 3, 4, 5, and 10 of the Climate Monitoring Principles.

Item 3 states that the metadata should be documented and treated with the same care as the data themselves. These projects provide the tools for efficient and user friendly data and metadata handling as well as enhancing the metadata record for each data set by providing additional quality assessments.

Item 4 states that the quality and homogeneity of the data should be regularly assessed. These assessments are at the core of these projects and would not be possible without the data management and synthesis efforts.

Item 5 states that consideration of the needs for environmental and climate monitoring products should be integrated into the global observing priorities. The synthesis and interpretation projects provide the products used by IPCC and others to assess the current state of the carbon cycle. This process then feeds back into the network design to ensure that data are collected in critical areas.

Item 10 states that data management systems should be included as essential elements of climate monitoring systems. The Ocean Carbon Data Management System (OCDMS) that is under development through these projects is an essential component of NOAA's Program for Building a Sustained Ocean Observing System for Climate. The OCDMS approach will utilize the standards and protocols advocated by the emerging Data Management and Communications (DMAC) subsystem of the US IOOS. As such the OCDMS will be fully compatible with the data and assimilation systems that will deliver routine ocean analyses through the international Global Ocean Data Assimilation Experiment (GODAE). It will be similarly integrated with the international ocean data frameworks, NOAA's Global Earth Observations Integrated Data Environment (GEO-IDE), the Observing System Monitoring Center (OSMC), the US GODAE Server and its climate data-serving partner the Asia Pacific Data Research Center (APDRC) through the National Virtual Ocean Data System (NVODS).

1.4 National and International Linkages

Recognizing the need to develop an international framework for carbon research, various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the Intergovernmental Oceanographic Commission (IOC), and the Scientific Committee on Oceanic Research (SCOR) have worked together to develop research strategies for global carbon cycle studies. The two primary international ocean carbon research programs are the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere (SOLAS) programs. Both programs strongly recommend a sustained carbon observing program. These programs are very supportive of NOAA's efforts to develop a Carbon Monitoring Network and a number of international colleagues have expressed interest in working with us to combine their data sets with ours. Because ocean carbon is relevant to so many international programs, IOC and SCOR have co-sponsored the International Ocean Carbon Coordination Project (IOCCP). The goals of the project are to gather information about on-going and planned ocean carbon research and observation activities, to identify gaps and duplications in ocean carbon observations, to produce recommendations that optimize resources for international ocean carbon observations and the potential scientific benefits of a coordinated observation program, and to promote the integration of ocean carbon observations with appropriate atmospheric and/or terrestrial carbon activities. Since Christopher Sabine is the chair of this project, NOAA's Carbon Monitoring Network is well integrated into the international coordination efforts. In addition to providing direct links to the international research programs, our involvement in the IOCCP provides a link to the global observing programs such as GOOS, OOPC, GCOS, and JCOMM.

The primary large-scale ocean carbon program within the United States is the Ocean Carbon and Climate Change Program (OCCC). All components of the NOAA Carbon Monitoring Network are intricately linked with other components of the OCCC. Coordination of these efforts is through C. Sabine and R. Feely who serve on the OCCC scientific steering committee.

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Because the Science Team, Data Management, and Synthesis projects are all working towards the common goal of improving our understanding of carbon cycle changes in the ocean, most of the progress is discussed in the Research Highlights section (section 2.4) and is not accredited to any of the 3 projects. In the first three sections we briefly list the activities of each project that have ultimately resulted in the highlights presented in section 2.4.

2.1 Science Team Accomplishments

2.1.1 PMEL (R. Feely/C. Sabine)

- Submitted A20/A22 cruise data to CDIAC.
- Submitted P2 cruise data to CDIAC.
- Performed preliminary quality control of A16S and P16S datasets.
- Participated in September Science Team meeting to discuss quality control procedures, standardization of data and metadata reporting, and sampling schedules for the next year.

a..2 AOML (R. Wanninkhof/T.-H. Peng)

- Evaluated the internal consistency of carbon measurements from A16S. Comparison of TAlk with TAlk calculated from pCO_2 and DIC is shown in Figure 1. The preliminary shipboard data showed an average difference of -2.03 ± 4.91 μmol kg^{-1} (N= 768). The agreement and precision is within the known uncertainty of analysis and significantly better than previous cruises.
- Data reduction and reporting for DIC, Talk, pH, and discrete pCO_2 has been completed for A16N, and is nearly complete for A16S. Details are shown in Table 1.
- A data reduction meeting held in Miami on October 5-6, 2005 resulted in consensus on the steps for automating QA/QC procedures for underway pCO_2 data at the regional level.

	A16N (2003)	A16S (2005)
Compile Dataset	completed	completed
Additional QC	completed	underway
Crossover Analysis	completed	completed w/ prelim. data
Final Data Calibration	completed	December 2005
Carbon Thermodynamics	completed	completed w/ prelim. data

Table 1. Status of data reduction and reporting for DIC, TAlk, pH, and discrete pCO_2.

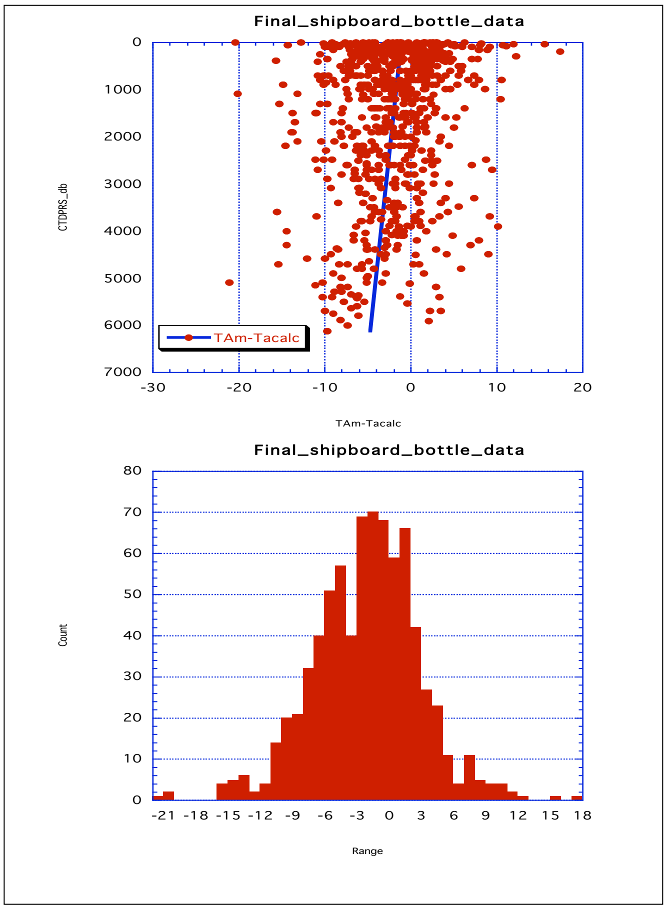

Figure 1. Comparison of TAlk with TAlk calculated from pCO_2 and DIC versus depth (top). The distribution of differences is shown as a histogram (bottom).

2.1.3 CDIAC (A. Kozyr)

- During FY 2005 CDIAC continued to obtain the new data from CLIVAR/CO_2 Repeat Hydrography Sections. By October 2005 CDIAC received data from 8 US and international Repeat Hydrography cruises that will be included in the synthesis work of this project. CDIAC developed a web site for CLIVAR/CO_2 Repeat Hydrography Sections at: http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html
- CDIAC published the NDP-085: Inorganic Carbon, Nutrient, and Oxygen Data from the R/V *Ronald H. Brown* Repeat Hydrography Cruise in the Atlantic Ocean: CLIVAR CO_2 Section A16N_2003a (4 June–11 August, 2003) – the first NDP for the Repeat Hydrography Sections.

2.1.4 Princeton (R. Key)

- During FY 2005 we obtained the new data from CLIVAR/CO_2 Repeat Hydrography cruises and incorporated these into the GLODAP dataset. By October 2005 we received data from 8 US and international Repeat Hydrography cruises.

2.2 Data Management System Accomplishments

2.2.1 PMEL (S. Hankin/J. Callahan)

- The database design is being improved to connect data records directly to the metadata associated with their collection and processing. This will allow for versioning of data through the integrated components of the data pipeline
- Scripts were written to ingest ASCII-formatted historic cruise data files from PMEL into the RDBMS;
- Underway data from PMEL (Ka'imimoana cruises prior to 2002) was used to populate a development version of the database to test the improved database design and new scripts for ingesting historic cruise data files. Examples of the products with the recently ingested Ka'imimoana data are shown in Figure 2.
- PMEL improvements to LAS in support of the OCDMS include the following:
    - Support for character strings (as opposed to numbers) in the LAS database support code. (This will allow data subsetting on metadata such as cruise ID, PI name, etc.)
    - Improved cruise plot visualization products.
    - Improved support for Macintosh browsers.
    - Improved use of data window pop-ups to avoid pop-up blocking.
    - Support for server-side analysis with the Ferret Data Server (FDS).
    - Graphics improvements including user settable contour levels, graticules, color palettes, etc.

- o Work on faster and more flexible "back end" design, which will be incorporated during FY06.

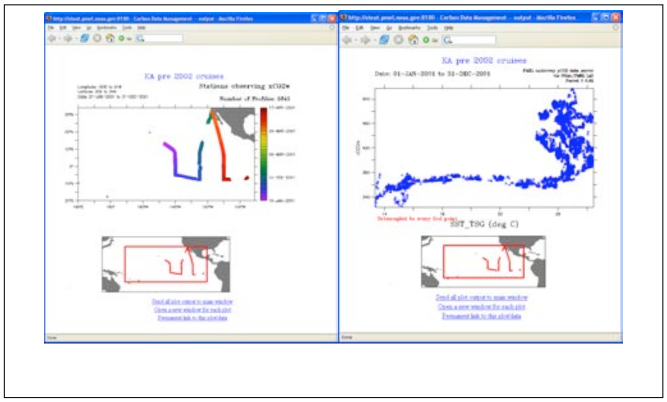

Figure 2. Plots obtained from LAS to visualize cruise tracks (left) and property-property plots of xCO_2 vs. SST (right).

2.2.2. CDIAC (A. Kozyr)

- A very important part of data evaluation and synthesis is obtaining and archiving the metadata for each data set. Individual PIs were contacted by CDIAC in order to obtain experimental details and quality control information related to datasets submitted to CDIAC. CDIAC implemented a new metadata management system called Mercury that consists of a Mercury search engine and OME (ORNL Metadata Editor). All CDIAC data holdings are searchable through the Mercury and each data set is complete with the full metadata information created using OME. CDIAC Mercury could be accessed at: http://mercury.ornl.gov/ocean/.

2.2.3. AOML (Peng/Wanninkhof)

- Results of the IOCCP sponsored workshop: "Ocean Surface pCO_2, Data Integration and Database Development" have been summarized in IOCCP documents recommending practices and formats for managing pCO_2 data.

2.3 Synthesis Project Accomplishments

2.3.1 PMEL (C. Sabine/ R. Feely)

- Estimates of anthropogenic CO_2 uptake over the past decade were calculated using data collected during cruises in 1994 and 2004 along 30°N in the Pacific Ocean.
- Estimates of anthropogenic CO_2 uptake over the past decade were calculated using data collected during cruises in 1997 and 2003 along A20/22 in the North Atlantic Ocean.
- Began investigating use of ARGO data to estimate basin-scale distributions of carbon using MLR empirical relationships to physical measurements.
- Began developing a carbon metric for the NOAA Carbon Monitoring Network

2.3.2 AOML (Wanninkhof/Peng)

- Completed a re-evaluation of GEOSECS carbon data in the Atlantic Ocean by examining deep water properties at crossover stations between GEOSECS and WOCE cruises has been completed.
- Estimates of anthropogenic CO_2 uptake over the past decade were calculated using data collected during cruises in 1993 and 2003 along A16N in the North Atlantic Ocean.
- Assisted with the development of a carbon metric for the NOAA Carbon Monitoring Network

2.3.3 CDIAC (A. Kozyr)

- Published GLODAP data set Version Gv.1.1 as a Numeric Data Package (NDP)-083. This data package consists of a printed GLODAP report, reprints of the most important publications that resulted from the GLODAP work, a DVD with Gv.1.1 data set, and the GLODAP web page. The Gv.1.1 data set is available free of charge from CDIAC. The data, and any subsequent updates, are also available through the GLODAP web site (http://cdiac.ornl.gov/oceans/glodap/Glodap_home.htm). The GLODAP bottle data files are available as ASCII files, in Ocean Data View (ODV) format, and through the CDIAC live access server (LAS); the gridded data files are available as ASCII files, ODV format, and NetCDF data file formats and through CDIAC LAS.
- Continued to identify historical data sets that could be included in the synthesis work. During last year CDIAC copied the unpublished CARINA (http://www.ifm.uni-kiel.de/fb/fb2/ch/research/carina/) data files that include discrete and underway carbon measurements in the Atlantic Ocean. The discrete data files were sent to Princeton for farther evaluation and synthesis. The underway data will be evaluated at CDIAC and will be used for future synthesis work.

2.3.4 Princeton (R. Key)

- CARINA
  - Data files have been obtained.
  - Data transformed into standard format, including units conversion
  - Primary quality control of all parameters
  - README files contained associated metadata created for each cruise
  - very preliminary data comparisons
  - Identified PIs who could/would work on each cruise and transferred files to PIs for further input
  - started to incorporate PI changes/updates and to accumulate data which was initially omitted from CARINA
- CARBOOCEAN - attended initial meeting and helped design data system
- Assisted with the development of a carbon metric for the NOAA Carbon Monitoring Network
- Assisted with investigation of using ARGO data to estimate basin-scale distributions of carbon based on MLR empirical relationships to physical measurements.

2.4 Analysis and Research Highlights

Because the three projects represented by this report are so closely connected, it is impossible to attribute the research highlights to any one project. All of the projects contribute to the analyses in one way or another and it is only through the combined efforts of all three can the final products be generated.

Our work on the changes in ocean carbon has progressed over the last year in three general directions: 1) enhancing the WOCE era datasets, 2) using WOCE era datasets to evaluate historical data, and 3) interpretation of new datasets with respect to WOCE era data.

2.4.1 Enhancing the WOCE Era Datasets

The CO_2 group represented by these projects (Carbon Monitoring Group) has worked together since 1990 to collect and analyze data from the NOAA/NSF/DOE Global CO_2 Survey cruises under the auspices of NOAA's Climate and Global Change (C&GC) Program. As part of this effort, we synthesized the CO_2 data from the Atlantic, Pacific and Indian Oceans into a unified self-consistent data set (Sabine *et al*., 1999; Feely *et al*., 1999; Lamb *et al*., 2002; Wanninkhof *et al.*, 2003; Sabine *et al.*, 2005), from which we have determined the distribution of anthropogenic CO_2 in the oceans (Sabine *et al*., 1999; Feely *et al*., 2001; Sabine *et al*., 2002; Lee *et al*., 2003; Sabine *et a*.,, 2004); and the relative impacts of soft tissue remineralization and carbonate dissolution on the distributions of carbon species in surface and subsurface waters. (Feely *et al*., 2002, 2004; Sabine *et al*., 2002; Chung *et al*., 2003). The NOAA Office of Global Programs and the Department of Energy jointly funded the previous CO_2 synthesis work. All of the suggested corrections for the Global CO_2 data sets are available at the GLODAP WWW site (http://cdiac.ornl.gov/oceans/glodap/Glodap_home.htm) The WOCE/JGOFS era datasets provide a baseline from which spatial and temporal comparisons of ocean dissolved inorganic carbon (DIC) and total alkalinity (TAlk) can be made, and form the basis of the combined GLODAP dataset. To maximize GLODAP's potential, a number of enhancements to the dataset are planned or are in progress.

Over the past two years the Carbon Monitoring Group has enhanced the GLODAP data set with new Atlantic Ocean data as part of our collaborative efforts with European scientists supporting the Carbon in the Atlantic (CARINA) synthesis efforts. The Carbon Monitoring Group is providing a careful analysis of the new data fields, property-property plots, isopycnal surface analyses, and multi-linear regression (MLR) analyses as part of our efforts to identify and to remove questionable data and to correct the data for cruise-to cruise-differences. Figure 3 shows the distribution of stations for which we have analyzed dissolved inorganic carbon (DIC) and total alkalinity (TAlk) data from the North

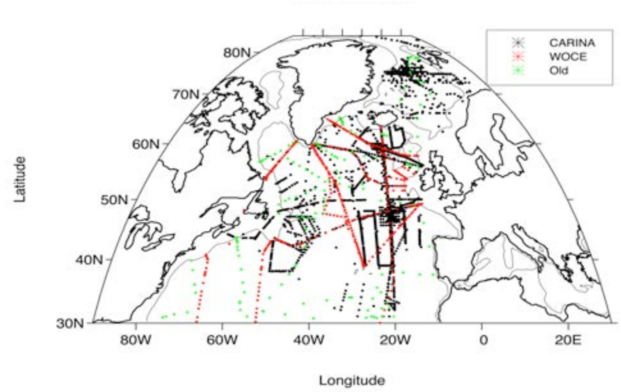

Figure 3. Locations of stations in the North Atlantic Ocean where DIC and TALK data have been analyzed for data quality and internal consistency.

Atlantic. To date, we have analyzed more than 33,000 sets of the new data to ensure they are maintained and preserved at the highest possible quality standards and to employ appropriate thermodynamic model calculations for CO_2 in seawater to calculate all of the remaining inorganic carbon parameters for each data set. The new data more than double the total number of samples for the North Atlantic. The final output will be a uniformly calibrated DIC and TAlk data set.

We are also in the process of evaluating and incorporating other data into the GLODAP data set including the recently released Beagle data from a Japanese expedition around the world at 32°S in 2003. One major activity has been the evaluation of data from a multi-year data collection effort by the Japanese Oceanographic Data Center (JODC). The JODC data include measurements of carbon from over 400 cruises in the North Pacific. This collection represents the most comprehensive assemblage of carbon measurements available for the North Pacific, with over 400 cruises from Japan, Taiwan, Canada, and the United States collected over the past few decades. However, it will take a great deal of effort to translate these data to a common format and evaluate the data quality.
The Carbon Monitoring Group is sharing the responsibilities of data gathering with our national and international partners. Drs. Feely, Sabine, Key, Dickson and Kozyr are working closely with colleagues from Canada, Japan, Korea, Taiwan and Australia to collect data for the Pacific Ocean. Drs. Key, Peng, Wanninkhof, Sabine, Millero, and Kozyr are performing similar duties for the Atlantic and Indian Ocean data sets. The data are sent to Dr. Key at Princeton who is performing the initial quality control analyses and integrates the data into the GLODAP database. For example, Figure 4 shows a TAlk versus salinity plot of the recently acquired data sets from the North Atlantic. The high degree of overlap of data between data sets is one indication of the good quality of the overall data. Flyers identified with this and other analyses under go further data quality checks in collaboration with the original measurement group.

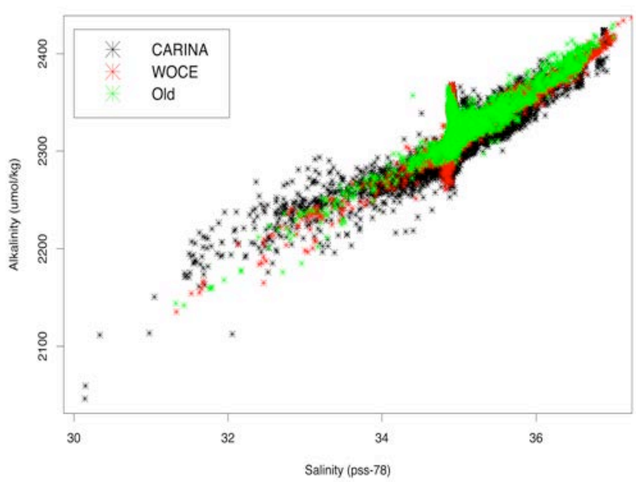

Figure 4. Plot of the TAlk versus salinity for three North Atlantic data sets north of 30°N in the new GLODAP database.

2.4.2 Using WOCE Era Datasets to Evaluate Historical Data

An important dataset whose addition provides a temporal component to the GLODAP compilation is the GEOSECS data. The carbon data collected during the GEOSECS program in early 1970s represent the first systematic survey of inorganic carbon parameters on a global scale. These data have become a critical component of studies of temporal variations of geochemical properties for the last 30 years. In particular, this dataset is useful to help quantify the oceanic uptake of anthropogenic CO_2 from the increase in DIC concentrations. However, it is essential that the historical data are consistent with recent high quality carbon data generated with improved measuring techniques and the use of reference material. An evaluation of the GEOSECS carbon

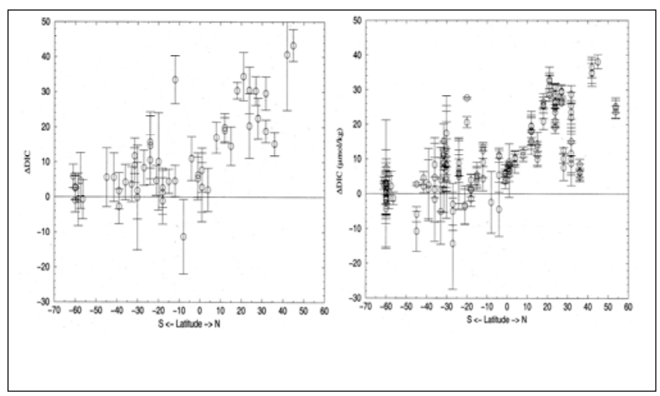

Figure 5. Atlantic ΔDIC (GEOSECS-WOCE) derived from MLR using deep water below 1500 m (left), and ΔDIC derived from Sigma-4 isopycnals at or below 1500 m (right).

data in the Atlantic Ocean was conducted by examining deep water properties at crossover stations between the GEOSECS and WOCE cruises. Based on the analysis of deep properties using both the deep isopycnal method and the multi-parameter linear regression methods of Lamb *et al.* (2001), we found that DIC and total alkalinity (TAlk) measurements made during GEOSECS program are systematically higher than those made during the WOCE/JGOFS global CO_2 survey in the North Atlantic. There is no significant difference in the South Atlantic. These results are shown in figures 5 and 6. The overall average offset of DIC in the North Atlantic is estimated to be 21.3 ± 12 µmol kg^{-1}, while the overall average offset of TAlk is 14.1 ± 7 μmol kg^{-1}. The corrected GEOSECS carbon data will be used to determine the uptake of anthropogenic CO_2 in the Atlantic Ocean in the last three decades.

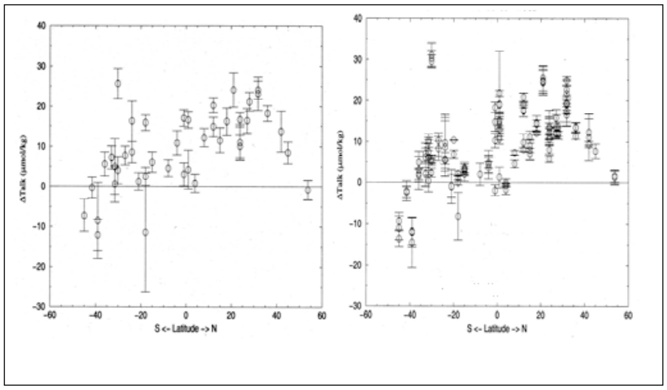

Figure 6. Atlantic ΔTAlk (GEOSECS-WOCE) derived from MLR using deep water below 1500 m (left), and ΔTAlk derived from Sigma-4 isopycnals at or below 1500 m (right).

2.4.3 Interpretation of New Datasets With Respect to WOCE Era Data

The international repeat hydrography program is generating new high-quality data that can be used to evaluate temporal changes in carbon (Figure 7). By repeating measurements along the WOCE lines of the 1980s and 1990s, the GLODAP dataset will be enhanced with this additional temporal dimension. We have begun examining the first US CLIVAR/CO_2 Repeat Hydrography cruises relative to the WOCE/JGOFS data to look for decadal changes in inventory.

P2 Cruise in the North Pacific

The P2 cruise commenced in June, 2004 from Yokohama, Japan and proceeded along 30°N, ending in San Diego. Seawater samples were analyzed on board ship for salinity, dissolved oxygen, nutrients, dissolved inorganic carbon, alkalinity, and CFCs. During the cruise 190 stations were occupied and ≈ 6,000 water samples were collected for analysis of all these parameters. Carbon data from this cruise were compared with carbon data collected along the same transect in 1994 to obtain ΔDIC estimates.

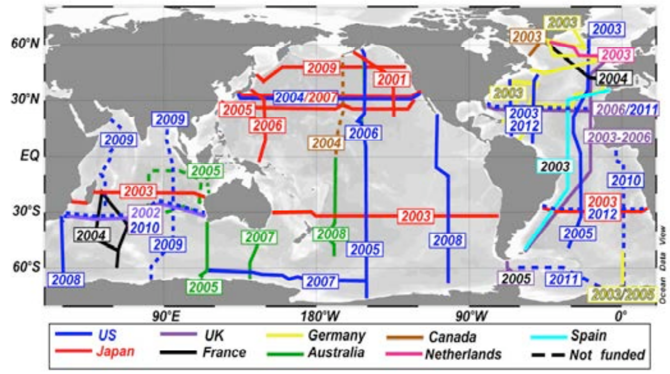

Figure 7. Proposed national and international Repeat Hydrography Program sections for the FY 2003-2012 period. For details on the US plan see: http://ushydro.ucsd.edu/

The difference between the measured DIC in the upper water column (150 - 1000 db) for the 2004 occupation and the 1994 occupation is shown in Figure 8A. A better method by which to obtain ΔDIC is to calculate a linear relation between carbon and commonly measured hydrographic properties (in this case: potential temperature, salinity, apparent oxygen utilization, silicate concentration, and phosphate concentration) in 1994 and then apply that relation to the 2004 dataset. We then utilized a multiple linear regression (MLR) analysis to further evaluate the difference between the two cruises (Figure 8B). Using the 1994 data set, commonly measured hydrographic properties were input into the MLR analyses as the independent parameters. Based on the relationship of DIC to those hydrographic properties, equation (1) was used to predict DIC from the 1994 hydrographic data:

$$DIC = a + b(t) + c(S) + d(AOU) + e(Si) + f(P) \qquad (1)$$

where *a*, *b*, *c*, *d*, *e*, and *f* are coefficients determined from the data, *t* is potential temperature, *S* is salinity, *AOU* is apparent oxygen utilization, *Si* is inorganic silicate concentration, and *P* is phosphate concentration. The total change in DIC between 2004 and 1994 is determined as the difference between the measured DIC values and those predicted from the 2004 hydrographic measurements utilizing the 1994 coefficients.

Similar procedures determined the change in anthropogenic DIC from Equations (2) through (4) where:

$$\Delta C_{ANTHRO} = \Delta C_{MEAS} - \Delta C_{ORG} - \Delta C_{TALK} \qquad (2)$$

$$\Delta C_{ORG} = (117/170) * (AOU_{MEAS} - AOU_{CALC}(MLR1994))$$

(3)

$$\Delta C_{TALK} = 0.5 * (TALK_{MEAS} - TALK_{CALC}\ (MLR1994))$$

(4)

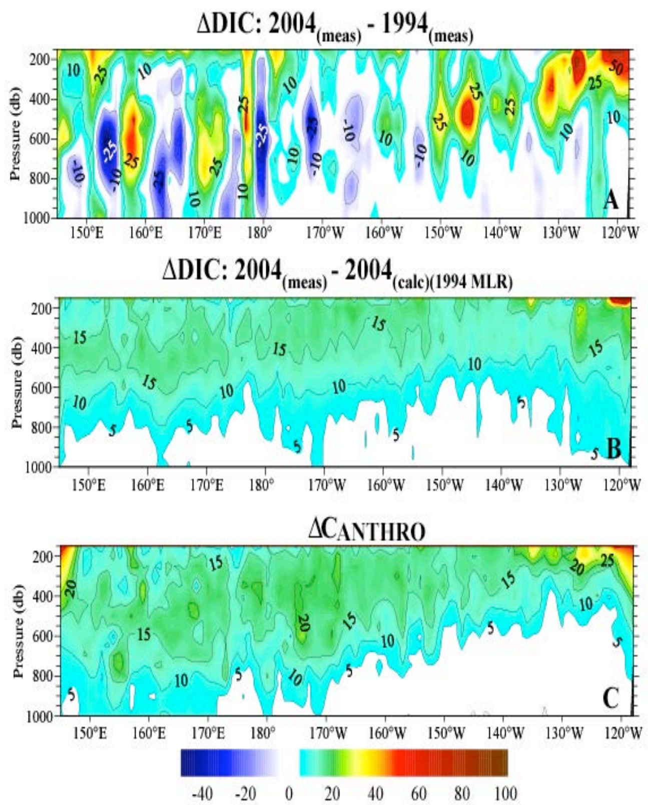

Figure 8. Measured and calculated ΔDIC (2004-1994) during P2 along 30˚N between 150 - 1000 db.

Figure 8C is the calculated anthropogenic uptake over the last decade. The values range between 0 - 50 μmol kg^{-1} with the largest differences occurring on the eastern edge of the basin.

The distribution of the rate of change of ΔC_{ANTHRO} versus sigma theta for the P2 data set is shown in Figure 9. The rate varies from 1.0 - 1.6 μmol kg^{-1} yr^{-1} between 100 - 700 db, and decreases to values close to zero near 1250 db. The increase at the base of the mixed layer is consistent with the results of the HOT data (see Table 2).

To facilitate a comparison of the North Pacific uptake rate estimates, we have combined a number of published results into Table 2. In some cases, the published values had to be converted to common units requiring assumptions about the area or integration depth. The results are divided into three categories: integrated water column uptake rate estimates, mixed layer increases, and surface pCO_2 increases. Most of the published values fall under the water column integrated uptake rate category, varying by region and depth range of integration; those values ranged from 0.25 - 1.3 mol m^{-2} yr^{-1}. The mixed layer uptake rate estimates were much more consistent, with values of 1.0 - 1.5 μmol kg^{-1} yr^{-1} based on direct observations and MLR approaches. These estimates are higher than similar estimates for the North Atlantic using the same methods. This may be the result of differences between the warm and cold phases of the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) in their respective basins (Feely et al., 2005).

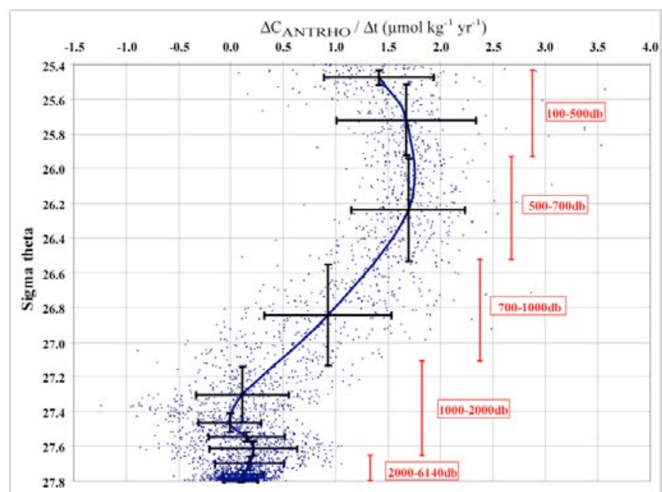

Figure 9. Rate of change of ΔC_{ANTHRO} as a function of sigma theta along the P2 30˚N transect.

A16 Cruise in the Atlantic

Changes in DIC and AOU are quantified by interpolating the 2003 A16N and 2005 A16S cruise data, and those of the cruises in 1993 and 1989, on 1° by 50 dbar grids and subtracting the two matrices. Most of the changes are observed in the upper water column (Figure 10).

The changes are caused by anthropogenic CO_2 entering the ocean but also by changes in the positions of fronts, eddies, remineralization, and ventilation as manifested by changes in water mass properties. DIC and AOU changes range from -5 to 40 μmol kg^{-1}. The AOU is unaffected by anthropogenic CO_2 invasion and therefore can be used to separate "natural" DIC changes from those caused by invasion of anthropogenic CO_2.

Conceptually this can be done by separating the total DIC increase into:

Integrated uptake rate (mol m^{-2} yr^{-1})	Mixed layer uptake (µmol kg^{-1} yr^{-1})	pCO_2 increase (µatm yr^{-1})	Approach	Area of Study	Years	Depth range (m)	Reference
0.83 ± 0.19	—	—	OBS	Northwestern Pacific	1973-1991	0-2000	Tsunogai *et al.* (1993)
—	0.4-1	1.8 ± 0.6	OBS	137°E, lat > 15°N	1984-1993	0	Inoue *et al.* (1995)
—	—	0.5 ± 0.7	OBS	137°E, lat < 14°N	1984-1993	0	Inoue *et al.* (1995)
0.63* ± 0.15	1.3 ± 0.7	—	MLR	Central North Pacific	1973-1991	125-1250	Slansky *et al.* (1997)
0.58 ± 0.09	—	—	CFC	North Pacific	1988-1998	0-cfc=0.02	Watanabe *et al.* (2000)
0.47 ± 0.2	—	—	OBS	Pacific	1982-1993	0-1000	Ono *et al.* (2000)
0.39 ± 0.1	—	—	CFC	Pacific	1980-1999	0-2000	McNeil *et al.* (2003)
1.0* ± 0.4	—	—	OBS	KNOT	1992-2002	200-700	Wakita *et al.* (2003)
0.7	—	—	OBS	HOT	1989-1992	0	Winn *et al.* (1994)
—	1.0 ± 2.9	—	OBS	HOT	1989-1995	0-60	Winn *et al.* (1998)
1.1 ± 0.1	1.2 ± 0.2	2.5 ± 0.3	OBS	HOT	1988-1999	0-225	Dore *et al.* (2003)
0.25	—	—	INV	13°N-36°N	1990	0-btm	Gloor et al. (2003)
0.46	—	—	INV	36°N-62°N	1990	0-btm	Gloor et al. (2003)
1.3 ± 2.1	—	—	MLR	North Pacific	1973-1991	300-1250	Peng *et al.* (2003)
—	—	1.8 ± 0.7	OBS	Equatorial Pacific	1990-2001	0	Takahashi *et al.* (2003)
1.1 ± 0.4	1.3 ± 0.2	—	MLR	Central North Pacific	1973-1999	0-1250	Feely *et al.* (2003)
0.74*	—	—	DC*	HOT	1989-2000	100-800	Sabine *et al.* (2004)
1.0 ± 0.6	1.4 ± 0.3	—	MLR	Central North Pacific	1973-2004	0-1250	This work
—	1.5 ± 0.2 <39°N	—	MLR	Central North Pacific	1973-2004	0-200	This work
—	1.1 ± 0.4 >39°N	—	MLR	Central North Pacific	1973-2004	0-200	This work

* = uptake not integrated all the way to the surface

Table 2. Estimates of carbon dioxide increases in the North Pacific Ocean

$$\Delta DIC = \Delta Canthro + Physical\ Circulation\ Changes + Biological\ Changes \quad (5)$$

The physical circulation changes and biological changes can be separated from ΔC_{anthro} if DIC, oxygen and nutrient levels vary in fixed stoichiometric ratios. This is an *a priory* assumption in the methods described below. However the separation techniques must be verified through use of transient tracers and/or numerical models.

Two methods are used to determine the anthropogenic CO_2 increase over the time interval. The first one determines the changes in DIC that correspond to changes in AOU and alkalinity, and the residual is assumed to be anthropogenic CO_2. This is done by using the quasi-conservative quantity C* (Gruber *et al.* 1996):

$$C^* = DIC_{obs} - r_{C:O2}\, O_2 - 0.5\,(Alk + r_{NO3:O2}\, O_2) \quad (6)$$

where $r_{C:O2}$ and $r_{NO3:O2}$ are the remineralization ratios for carbon and oxygen (=117: -170) and nitrate and oxygen (16: -170), respectively. The C* for 2003/2005 and the 1993/1989 cruises are calculated and the difference is assumed to be the C_{anthro} increase over the time period.

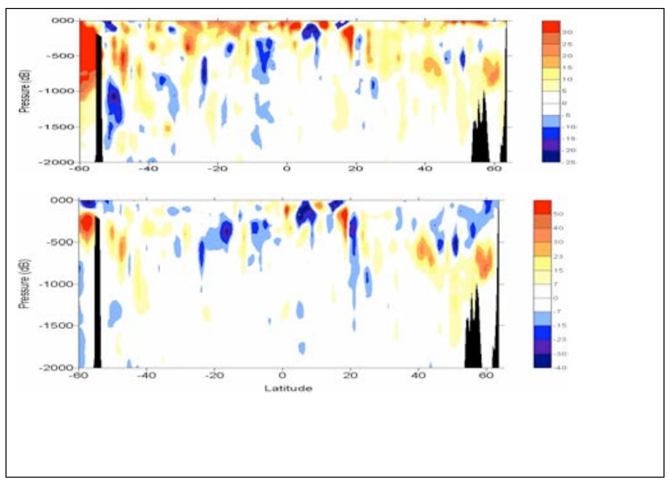

Figure 10. Changes in DIC (top) and AOU (bottom) in the upper 2000dbar of the Atlantic (south is 2005-1989; north is 2003-1993). The units are µmol kg^{-1} and the AOU color bar is approximately scaled by the Redfield ratio (AOU: C = 170:116) such that the color scheme of the two figures correspond.

The second method is the multi-linear regression

(MLR) approach where DIC is regressed linearly with potential temperature, salinity, AOU, nitrate and silicate (Peng *et al.*, 2003) for data at depths > 250 dbar. Changes in DIC $_{anthro}$ are determined using two variation of the MLR:

1. The DIC_{MLR} is determined from the 2003/05 Temp, Salt, AOU, NO_3 and Si data using the 1989/93 algorithm. This value is subtracted from the measured 2003/05 DIC value (DIC_{2005}- MLR_{1993}).

2. The DIC_{MLR} is determined from the 2003/05 Temp, Salt, AOU, NO_3 and Si data using both the 1989/93 and the 2003/05 algorithm and these values are subtracted (MLR_{2005}- MLR_{1993}). The results are shown in Figure 11.

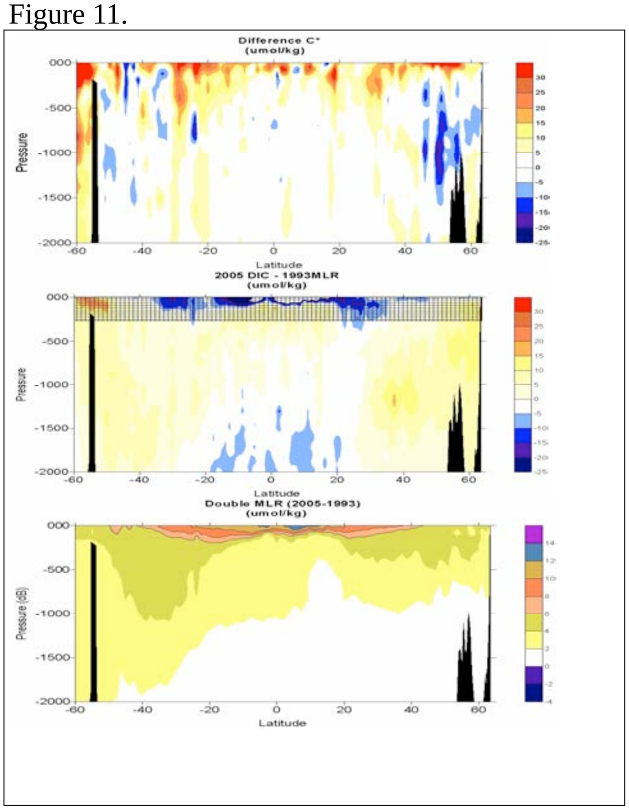

Figure 11. Patterns of change in anthropogenic CO_2 in the upper 2000 dbar using the C approach (top) and two variations of the MLR approach (middle and bottom). For the MLR, data > 250 dbar are used to create the multi-linear regression and this interval is indicated by hatch marks in middle panel.*

The changes in the upper water column are summarized in Table 3. Values are shown per annum to account for the difference in time between the reoccupations for the North Atlantic (10 years) and South Atlantic (15 years). The total change DIC_{antho} for the methods are in reasonable agreement. The change DIC_{antho} is also close to the change in DIC suggesting that for the whole transect there are no large systematic changes in biological processes or circulation. However the patterns of uptake are quite different for the different approaches. Particularly in the North Atlantic the C* difference suggests a loss of C_{anthro} in the upper Labrador Sea water (700 dbar) while the single MLR method suggests a significant uptake (Figure 11). This different behavior is attributed to changes in ventilation pattern causing a large increase in AOU over the past decade in the region (Johnson *et al.*, 2005). This increase in AOU does not have an associated DIC increase in proportion to Redfield stoichiometry. The double MLR shows an increase in a similar pattern as storage of the entire anthropogenic CO_2 burden in the ocean with greatest changes in storage in the subtropical gyres (Lee *et al.* 2003, Sabine *et al.*, 2004).

Table 3. Change in specific inventory of DIC, AOU, and C_{anthro} for A16 section (mol m^{-2} yr^{-1})[1]

	Average[2]	**St. Dev.**[2]
Change in DIC inventory	0.70	1.07
Change in AOU inventory	0.11	0.91
Change in C* inventory	0.90	1.04
2005 DIC-1993 MLR[3]	0.55	0.97
2005 DIC-1993 MLR (250 m)[4]	0.69	0.92
2005 MLR-1993 MLR	0.68	0.18
Air-sea gas exchange[5]	0.97	0.4
Global air-sea CO_2 uptake rate[6]	0.4	0.2

1: The specific inventory changes are determined per annum using a time interval of 15 years for the South Atlantic and 10 years for the North Atlantic.
2: Average and standard deviation determined from the gridded data with grid spacing of 1˚ latitude and 50 dB depth.
3: Applied the MLR to surface while the coefficients were created from 1993/1989 data for depths greater than 250 dbar.
4: Applied the MLR to depths greater than 250 dB and extrapolated the values at 250 dB to the surface.
5: Increase in DIC along the transect if uptake was solely determined by air-sea gas transfer and assuming an atmospheric increase of 1.6 ppm yr^{-1}. The NCEP monthly winds and monthly climatological SST are used. This should be considered an upper limit for illustrative purposes only.

6: Specific Global uptake rate based on an annual uptake of 1.6 Pg C yr^{-1} for illustrative purposes only.

All of the results presented here are still works in progress and will likely be revised before final publication. They are presented here primarily to illustrate that the practice of interpreting data from a measurement network is a scientific process that takes time and effort to develop properly. We also see that procedures that appear to work well in some ocean regions do not necessarily work well in other areas where regional conditions are different. The Carbon Monitoring Group is continuing to work together with national and international colleagues to gather high-quality data, to synthesize these data into a global carbon dataset that the community can utilize for carbon cycle studies, and to develop the science behind the interpretation of temporal changes in the ocean carbon system.

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16. Arctic Ice Thickness: State of the Arctic Report

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PROJECT SUMMARY

Objective

This work directly supports NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate, by expanding current efforts to monitor and document the state of the ocean to include the Arctic Ocean. The first step in achieving this objective is the preparation of a baseline State of the Arctic Report.

Rationale

Recent observations are consistent in their indication that the Arctic region is undergoing significant environmental changes caused by a general warming of the climate. The heightened sensitivity of this environment is due, in part, to strong feedback processes that exist over both the ocean and land and are unique to this region. For instance, the Arctic Ocean is distinguished by the presence of a sea ice cover. Strong and complex interactions between the atmosphere, ice, and ocean, result in powerful feedback mechanisms such as the ice-albedo feedback. Similar snow-albedo feedbacks are likely to exist over the landmasses. Another example of a powerful positive feedback mechanism relates to permafrost degradation and consequent greenhouse gases release from the thawing soils and, possibly, gas hydrates. These amplifications create an environment that acts both as an indicator of climate change and as a potential amplifier of climate change. Because of this and the key role the polar regions play in determining the global climate, it is important to describe and to understand the state of the Arctic.

Approach

We seek to provide an annual, peer-reviewed consensus report and conclusion summary, which highlights major changes in the Arctic that are of particular interest to the greater climate change community. The benchmark assessment will be based on data obtained from U.S. and international sources. It will be a pan-Arctic description of the key atmosphere, ice, ocean and land parameters including:

- Atmospheric circulation
- Surface air temperature and barometric pressure
- Sea ice drift, concentration, thickness, extent, and surface conditions
- Arctic Ocean circulation, thermohaline structure, and heat content
- Ocean transport of freshwater, heat and nutrients through major Arctic gateways
- Sea level
- Biological activity from primarily productivity to fish to marine mammals
- Snow cover extent over the landmasses and changes in terrestrial hydrology
- Thermal state of permafrost and active layer thickness
- Changes in terrestrial ecosystems

Specific steps to be taken in preparing the report include:

1. Collection of input from national and international Arctic experts
2. Hosting a workshop on the state of the Arctic
3. Preparing a baseline report on the state of the Arctic
4. Developing a methodology for an annual reassessment
5. Widely disseminating the report

During the workshop the participants will evaluate different data sets, which have been collected prior to the workshop, and to reach consensus and synthesis on the current state and outlook for the Arctic. The report will be prepared, based on the workshop, and available to NOAA in early December. We will also post the report on Web, present highlights at major conferences, and prepare a paper for submission to a peer-reviewed journal.

Throughout this effort we will make effective use of the Internet for enhancing science team communication, for background material searches, for report preparation, and for widely conveying our findings. This will include a separate educational outreach section directed at the general public that will present information on the changing Arctic in a clear and accessible fashion.

FY2005 PROGRESS

This project marks a new start in FY2005. A workshop to assist in formulating the report has been scheduled for 24-26 October 2005. It will be held at the Woods Hole Oceanographic Institute, Woods Hole, MA. . The workshop will include invited presentations by team members on the state of key atmosphere, ice, ocean and land parameters, as well as small discussion sessions (Appendix A: Workshop Agenda). Lead authors for each section of the report have been selected: Jacqueline Richter-Menge (CRREL: Sea ice), James Overland (NOAA PMEL: Atmosphere), Andrey Proshutinsky (WHOI: Ocean), and Vladimir Romanovsky (UAF: Land). A science advisory team, consisting of 9 national and international Arctic experts from universities and government laboratories will join these lead authors at the workshop (see Appendix B: List of Workshop Participants). Input, which will serve as the basis of presentations and discussions at the workshop, has been collected from scientists within the Arctic research community. Relevant background material for the workshop has been posted on the existing Arctic Change Detection website (http://www.arctic.noaa.gov/detect/), which will also be used in the preparation and dissemination of the final report.

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17. Observing System Research Studies

D.E.Harrison
NOAA/Pacific Marine Environmental Laboratory, Seattle, WA

PROJECT SUMMARY

This project supports the design, development and evolution of the global ocean observing system for climate. An effective observing system must be built around what is known about the space and time scales and uncertainties of the climate signals of interest, relative to the background oceanic variability. Design and development results are accomplished through a variety of data analysis and modeling studies intended to expand our knowledge about what we know and what we cannot know from the observing system as deployed and the historical data set that has been produced over the decades. The evolution of the observing system is guided through studies of alternative observing strategies and evaluation of the differences between available ocean analysis products (taken as one measure of the uncertainty in these products). Some studies also have been carried out to establish the societal relevance of indices based on accurate, sustained global ocean observations and analyses of these observations.

Finally the Office of Climate Observations and NOAA's ocean and climate observing goals are supported through the PI's activities as Chair of the intergovernmental Ocean Observations Panel for Climate (cosponsored by the GOOS, GCOS and WCRP) and other national and international sustained ocean observing and science leadership activities. The PI also contributes to the development of international global operational oceanography as a member of the JCOMM Management Committee and work with several of its Program Areas, including the Observation Coordination Group.

Initial focus has been on SST variability since it is agreed to be the most important variable for climate impacts. This work continued during FY05 and was extended to include initial studies of the status of ocean sea ice knowledge. During FY05 significant effort was also devoted to studies based on the historical ocean subsurface temperature. data base with other variables will be expanded in the coming year as described below.

FY05 PROGRESS

Summary and Overview

Overall, the work of the group provided a variety of scientific and social impact justifications for continuing the deployment of the planned global climate observing system. Progress continued to be made on defining the space and time scales of observations needed for specific phenomena that must be accurately observed. Some progress also was made on the development of an initial set of ocean climate indices.

The Indian ocean remained a focus of activity, because NOAA plans to extend the tropical mooring array into this ocean in FY06. Indian continental rainfall and its dependence on SST anomalies is one of the primary societal impacts, as almost one billion people depend on the Southwest monsoon's rainfall. Rainfall variability in eastern tropical Africa also is very important to the peoples of that area.

The Vecchi and Harrison paper is the first, to our knowledge, to establish sampling criteria for the tropical Indian Ocean for ocean temperature profiles. (This work was completed at GFDL but is listed here because it was begun while Dr. Vecchi was at PMEL.) A model of the tropical Indian ocean was developed, based heavily on the tropical Pacific model refined over the past decade by Harrison and collaborators, and tuned to reproduce many aspects of the observed seasonal cycle near the equator. Model output was subsampled in various ways to explore whether the normal 10 day sampling interval for Argo floats would resolve satisfactorily the strong subseasonal variability in the region, or whether a shorter interval would be needed. It was found that 10 day sampling appears to be adequate for intraseasonal time scales if Argo floats are sufficiently dense in space.

Work continued on the space and time scales, and mechanisms of formation of Indian ocean SST and SST anomalies. Andy Chiodi will defend his PhD thesis in late 2005 or early 2006, which focuses on these issues. The first paper from his thesis work has been submitted, on a new mode of summer subseasonal southern hemisphere anomalies, Harrison and Chiodi (2005a). A second paper is nearly ready to be submitted, on why the seasonal range of SST (Max SST minus Min SST) is maximum in middle southern latitudes. The third paper will address the mechanisms responsible for the southern hemisphere SST anomalies that have been linked to eastern African precipitation variability.

The TRMM TMI and AMSR-E SST data sets, based on microwave SST retrievals have been essential in the Indian Ocean work, because they permit observation of SST anomalies under many types of cloudy conditions. SST is not observable by IR techniques under these conditions. The work of this project thus makes a strong case for the importance of continuing access to TRMM quality microwave SST information as a component of the global ocean observing system.

Work on equatorial Pacific SST variability also continued during FY05. Previous work into the relationships between westerly wind events (WWE), the Madden-Julian Oscillation (MJO) and waveguide SST warming has been updated. The relationships that were found previously, but which were of marginal statistical significance are now clearly statistically significant. They establish that WWEs are no more likely to occur during an MJO than they are when an MJO is not present, that waveguide warming follows the passage of an MJO only when a WWE occurs during the MJO but that WWEs, if they occur during an MJO, are more likely to occur during the convective phase of the MJO. Together with the earlier published work that establishes a dynamical connection between WWEs and waveguide warming, this work strongly suggests that observing and predictive attention should be given to WWEs and not to the MJO, if El Nino prediction is the objective. High time resolution observations are essential to proper characterization of WWEs; the TAO/Triton moorings remain key to this capability.

Predicting the termination of El Nino events is another objective of NOAA's seasonal to interannual prediction efforts. Via a series of ocean numerical model studies, the processes responsible for the termination of the 1997-98 and 2002-03 El Nino events have been identified. In each case the mechanism appears to be that proposed by Harrison and Vecchi (1999), in which the coupled interaction between the seasonal meridional cycle of solar insolation and near-equatorial SST anomalies, and the zonal wind anomalies associated with the resulting SST anomalies near the Dateline, is key. Delayed oscillator processes are not necessary to account for the observed oceanic behavior. The state of cold tongue zonal winds at the height of the El Nino determines whether the oceanic response to the zonal wind anomalies will lead to termination of the El Nino in early Spring (as happened in 2002-03), or if the El Nino will continue into late Spring (as happened in 1997-98 and 1982-83). Again, accurate near-equatorial wind and SST knowledge, such as is obtained from the TAO/Triton array, is key to successful prediction.

Work has also continued in the use of TAO/Triton data to test existing models of the equatorial Pacific. It was found previously that the Gent/Cane intermediate model cannot be reconciled with the observations, when used with the limited vertical resolution that has been adopted so far in model studies using this formulation. A similar result was found using the somewhat more physically complex Gent-Cane "intermediate" model of the tropical ocean. The mooring data have been essential to this study, providing an important result for the relevance of intermediate coupled models for study of El Nino predictability and processes.

The importance of high latitude information for US seasonal weather anomaly forecasting has been given a new twist by our discovery that the weather anomalies, particularly over the eastern half of the US and over Alaska during an El Nino winter depend strongly on the sign of the Arctic Oscillation (AO). Further we have found that there is a reasonable statistical basis for Winter AO forecasting, given knowledge of autumn AO conditions. We have communicated this result at national meetings and to L. Uccelini. Accurate knowledge of the AO thus appears key to improved US winter weather forecasts. It may be that improved knowledge of MSLP over the Arctic will lead to improved understanding of the AO and improved means for its seasonal prediction.

The importance of having substantially enhanced global coverage of subsurface ocean data has been made clear by the MS thesis work of Mark Carson. In this work the historical ocean data base was examined to identify those grid boxes where there was sufficient data in time to define a statistically significant temperature trend over the period 1950-2000. It was found that even at 100m depth, much less than half the ocean has sufficient data, and was shown that, of the boxes where such data density is found, roughly half of them involve warming trends and half cooling trends. It was not sensible to attempt to estimate global ocean temperature trends. At 300m and 500m much less of the ocean had sufficient data. Runing 20-yr trends also were estimated and it was found that there is lots of decadal time scale trend variability, which makes it clear that it is unwise to extrapolate trends based only on the recent satellite data era (~20years) to longer term trends. This work establishes the importance of additional work to estimate the uncertainty in recently published global ocean temperature trends, and makes very clear the contribution that completing and sustaining the global Argo array of profiling floats will make to important matters like knowledge of subsurface ocean temperature variability and trends.

18. Simulation of the ARGO Observing System

Edward S. Sarachik and I.V. Kamenkovich
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PROJECT SUMMARY

The main goal of this project is to examine how well the ARGO observing system determines the state of the global upper ocean. To this end, we sample and reconstruct oceanic fields from ocean general circulation models (GCMs) in gradually more realistic sequences of simulations. By quantifying errors in the reconstructed fields, we estimate accuracy of the ARGO observing system, and therefore directly address NOAA's Program Plan for *Building a Sustained Ocean observing System for Climate*.

We have (with Drs. Wei Cheng and D.E. Harrison) been looking at the expected performance of the ARGO observing system for the ocean. We have started with a course resolution global ocean GCM in order to (i) train ourselves for higher resolution models and (ii) see if there is anything in the coarse resolution model the ARGO system could *not* resolve to identify direct limitations of the system.

The GCM (*Kamenkovich* 2005) has a horizontal resolution of 2 degrees in both latitude and longitude and 25 vertical levels. Heat fluxes into the ocean are determined using conventional bulk formulas. Daily values for the 2-meter air temperature and humidity, 10-meter wind speed, and zonal and meridional components of the wind stress are taken from years 1979-2001 of the NCEP-NCAR reanalysis. Climatological monthly values are used for all other atmospheric variables. Cloud cover and solar radiation are taken from the International Satellite Cloud Climatology Project. Climatological monthly values of freshwater fluxes are used together with weak restoring of the surface salinity to Levitus climatological values. The model is coupled to a thermodynamic sea ice model. The simulated ocean state is as realistic as could be expected in a coarse resolution model; see Kamenkovich (2005) for further details.

We began by analyzing how the spatial distribution of the floats affects the performance of the ARGO observing system. We looked at two simple sampling considerations: (i) "parked-float" case, in which the float locations are fixed in time, and (ii) the "random-sampling" case, in which the floats are randomly re-distributed every time sampling takes place. In reality, the ARGO floats are advected with both the steady large-scale currents and high-frequency mesoscale eddies, and the most realistic scenario is expected to be in between these two limit cases. To simulate the actual ARGO sampling procedure, we sample simulated temperature and salinity every 10 days, and up to the 1500 meter depth. From the resulting "measurements", temperature and salinity of the ocean is reconstructed using objective analysis.

Overall performance of simulated observing system is good, and the reconstructed climatology of the temperature and salinity are very close to the actual GCM-simulated values (fig. 1a,b). However, both cases exhibit similarly significant differences between the reconstructed and actual fields within western boundary systems, such as the Gulf Stream and Kuroshio, and the Antarctic Circumpolar Current (ACC). These differences are smaller in the random-sampling case, due to a greater overall spatial sampling coverage (fig. 1b).

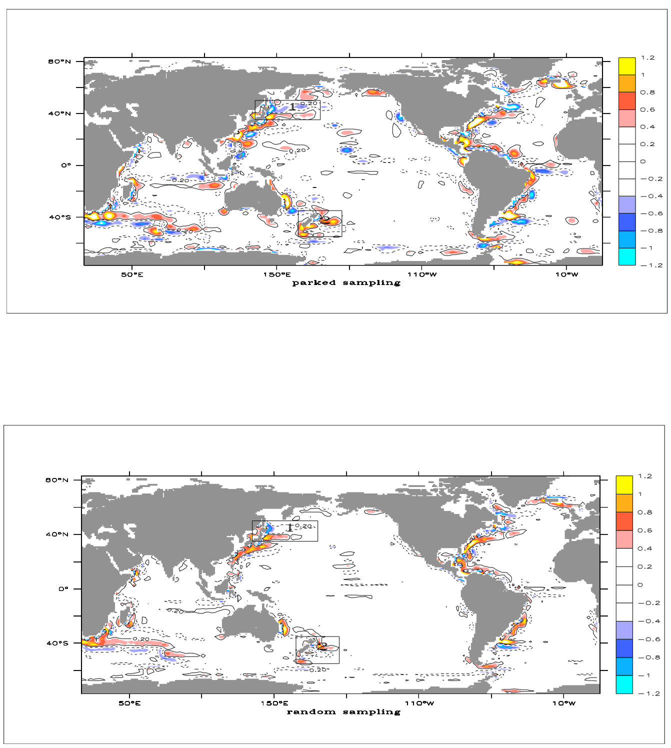

Figure 1 Difference between the reconstructed and GCM-simulated time-mean temperatures at 100 meter depth for: the "parked-float" case (upper panel) and the "random-sampling" case (lower panel). The sampled values are objectively analyzed to the original GCM grid.

Since these regions are characterized by swift oceanic currents and sharp spatial gradients whose intensity is underestimated by our coarse-resolution GCM, the deviations of the reconstructed fields from the actual values are expected to be even greater in reality than in our simulation. This result emphasizes the need for additional, dense spatial sampling in the vicinity of the western oceanic boundaries and in the ACC.

GCM-simulated temperatures exhibit significant month-to-month variability, which decreases in amplitude away from the surface (fig.2). The parked-float sampling method results in reconstructed temperature, whose variability is very similar in magnitude to the actual GCM-simulated values. In contrast, the random-sampling case overestimates the month-to-month variability for the following reason. Since the accuracy of the reconstruction method at any given point depends on the spatial distribution of the ARGO floats, random change of float position introduces an additional source of random errors in the reconstructed fields.

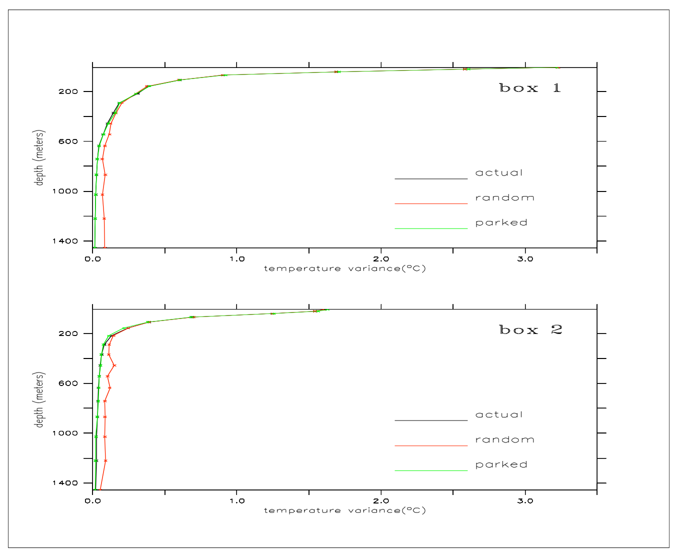

Figure 2 Standard deviations of the monthly temperature anomalies averaged within the two regions marked in Figure 1: Kuroshio system (Box 1, upper panel) and ACC region next to the New Zealand (Box 2, lower panel) as functions of depth. Climatological seasonal cycle is removed. The black lines show the actual GCM-simulated values; red lines – values reconstructed from a "random-sampled" case; green lines – values reconstructed from the "parked-float" case.

1. Observing System Monitoring Center (OSMC)

Steven Hankin[*1], Kevin J. Kern[*2], Ray ("Ted") Habermann[*3]
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PROJECT SUMMARY

The Observing System Monitoring Center (OSMC) system is an information gathering, decision support, and display system for the National Oceanic and Atmospheric Administration's (NOAA) Office of Climate Observations (OCO) located in Silver Spring, MD. It is an essential component of a sustained Ocean Observing System for Climate, that permits many discrete components to be visualized and managed as a system. The OSMC system displays current and historical status of globally distributed meteorological and oceanographic data collection systems. The OSMC system provides data visualization tools to identify the coverage of any given collection of platforms and parameters. These visualization tools are available via the internet and can be used to present information from OSMC to other NOAA centers, national partners, and international partners. The OSMC system can be accessed through the use of a conventional web browser (e.g. MS Internet Explorer). The system can be accessed by following the links from the OCO Web page (http://www.oco.noaa.gov) or accessed directly at the following URL: http://osmc.noaa.gov/OSMC/.

The OSMC project is a joint development effort between the National Data Buoy Center (NDBC) located at Stennis Space Center in Mississippi, the Pacific Marine Environmental Laboratory (PMEL) located in Seattle Washington, and the National Geophysical Data Center (NGDC) located in Boulder Colorado. Funding is provided by OCO under the direction of Mr. Mike Johnson. The project is aligned to take advantage of the strengths of each organization. NDBC (an operational organization) is responsible for the data; PMEL (a scientific organization) is responsible for the user interface/graphics/analysis tools; and NGDC (a data center) provides consulting services on the optimal use of data bases and GIS interfaces. PMEL has taken advantage of their existing tools Live Access Server (LAS), and Ferret (a data visualization and analysis tool) in the development and support of OSMC. NDBC has leveraged its investment in Oracle to support the OSMC database. NGDC utilizes databases and GIS systems to provide public access to numerous datasets.

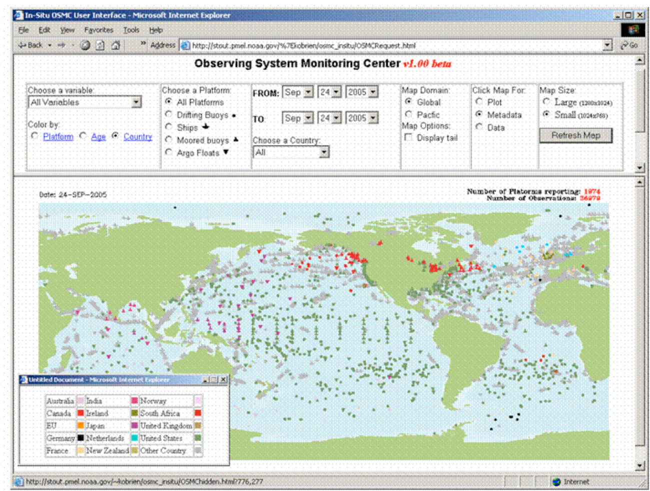

Figure 1. Screen snapshot of OSMC interface

Figures 1 and 2 show sample displays from the current OSMC system.

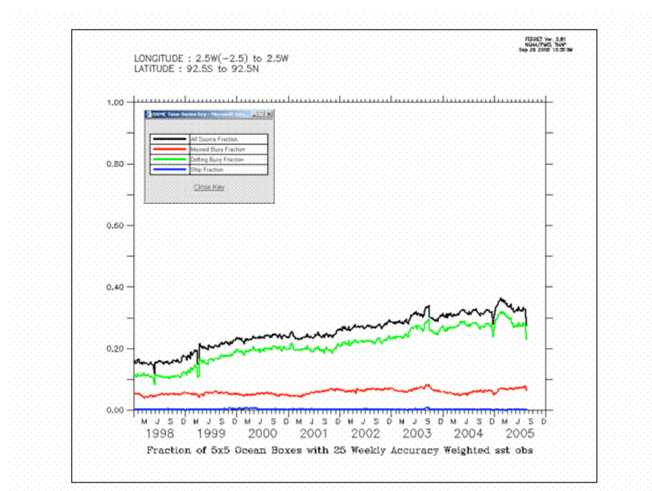

Figure 2. Progress in implementation of the ocean observing system

The scope of the OSMC system is not limited to NOAA data. It provides visualization and assessment tools for the international observing system as a whole. The OSMC is being designed in close cooperation with the JCOMM in situ Observing Platform Support Centre (JCOMMOPS). The development of the OSMC represents an important step towards the fulfillment of commitments to the Ten Climate Monitoring Principles.

FY2005 PROGRESS

The following progress was made on OSMC during fiscal year 2005.

All

- Presented an OSMC overview at the NOAA Climate Observation Program 3rd Annual System Review in Silver Spring (April 25-27, 2005). Solicited feedback from the Climate Observing System Council (COSC).

- Presented a poster on OSMC at the GODAE 2nd International Symposium, November 2004 in St. Petersburg, Florida

- Presented overview of OSMC at the annual meeting of the Global Organization for Earth System Science Portals (GO-ESSP) hosted by the British Atmospheric Data Center (UK)

- Held OSMC technical meeting Aug. 18 at PMEL, Seattle

PMEL accomplishments

- Developed v1.00 beta OSMC system for individual observations. This system offers a nearly complete suite of OSMC functionality for the in-situ observations
  - Selection of observations based upon parameter measured, type of platform, country of origin, date range
  - Map outputs with intelligible icons for platform types with options to color icons by country of origin, time since observation, or platform type and an option to show drifter tails
  - Drill down functionality to see tables of plots of data values, platform information (metadata), or drift plots
  - Configurable map size to address different desktop and laptop screen resolutions
  - Uses remote connection to OSMC Oracle database maintained at NDBC
  - Based upon Liver Access Server version 6.51

- Developed v1.00 OSMC alpha system for gridded visualization and analysis. This system offers an overview and initial tools with which to evaluate the performance of the observing system
  - Summary maps showing numbers of observations received by time period, parameter measures and resolution (1x1, 3x3, 5x5 boxes)
  - Summary maps showing percentage of time that regions (1x1, 3x3, 5x5 boxes) reach specified thresholds of observation density
  - Time series showing numbers of observations and/or percentage of times in which thresholds are achieved for boxes (1x1, 3x3, 5x5), ocean basins or global
  - Initial linkages to NVODS reference datasets, which were anticipated for FY05, were not completed due to the greater than expected difficulty at arriving at the initial user interface design through a distributed collaboration. This goal will be achieved in FY06.

- Released and supported the Adopt-a-Drifter web site and made numerous enhancements on request to provide educational opportunities for teachers to incorporate observing systems awareness into their curriculum. The Adopt-a-Drifter site accesses the functionality of the OSMC system for individual observations, including the Oracle database maintained by NDBC.

- Finalized software procedures to perform monthly (currently) updates of static images using NDBC OSMC database and NDBC systems.

- Continued to support updating of gridded data summaries, animations, pre-created graphics as needed to document the growth in performance of the Observing System.

NDBC accomplishments

- Provided database access functionality for the v1.00 beta OSMC

- Monitored the daily ingest of Met and Ocean surface data from GODAE into the OSMC database.

- Implemented daily updates of the 1x1 degree gridded files from the OSMC database.

- Added Ocean profile data to OSMC database.

- Improved Metadata by (1) importing the ship call information from WMO Pub47, (2) updating profiling float data with metadata from JCOMMOPS, (3) updated the metadata for NDBC stations/ partners based on NDBC website content.

- Procured an Oracle processor license to allow unlimited access to the OSMC data via the web.

- Held preliminary discussions on adding carbon data as a new data source for OSMC.

- Assisted in query optimization.

- Performed OSMC server upgrades and security patches as required.

NGDC accomplishments

- Established a database link between NDBC and NGDC and designed and implemented a daily "snapshot" upload of the most recent five days of data (daily upload at midnight, Mountain Standard or Daylight Savings time).

- Created spatial objects from the observation and platform locations using Oracle Spatial 10g. Used in conjunction with ESRI SDE 9.0, the data were spatially-enabled for map viewing and spatial queries.

- Connected existing database quality assessment tools to the OSMC database at NGDC. Used the tools to characterize existing database content. See, http://map4.ngdc.noaa.gov/idb/struts/tableMetadata?table=OSMC.OBSERVATIONS_MSQP&table=OSMC.ORGANIZATION_MV&table=OSMC.PLATFORMS_MSQP&sourceId=101583.

- Connected existing Rich Inventory and web-based monitoring tools to the NGDC database. See http://wist.ngdc.noaa.gov/wist/RiOsmc.jsp

- Created a "proof-of-concept" ArcIMS map viewer in a development environment. OSMC data may be viewed in a map using a standard Web browser, and the map includes basic GIS functionality such as pan, zoom, and searches. See http://mapdevel.ngdc.noaa.gov/website/naa/osmc.

- Evaluated initial database design and proposed modifications that address large amount of null values in the existing database and suggested optimization techniques

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2. Data-Assimilating Model Development

Bruce Cornuelle
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PROJECT SUMMARY

The objectives of the Consortium on the Ocean's Role in Climate (CORC) are: (1) to develop new observational and data assimilation methods for documenting and diagnosing ocean climate variability and (2) to maintain developmental elements of the ocean climate observing system.

New observational techniques being developed include an underway CTD, underwater gliders, data-assimilating models for observational synthesis and forecast initialization, and improved and tested conductivity sensors for use on profiling floats.

Data assimilating numerical ocean models have already proven a powerful way to combine disparate ocean observations of different quantities into a dynamically consistent analysis. The SIO data assimilation system is based on the MIT General Circulation Model (GCM) and uses and adjoint methodology to assimilate data while retaining dynamical consistency. We believe that, when perfected, dynamically consistent data assimilation will be the best way to initialize models and to analyze the dynamics of ocean climate variability.

FY 2005 PROGRESS

The goal of our effort is to use the ECCO assimilation system, which is based on the MIT general circulation model and its adjoint, to dynamically merge the Consortium for the Ocean's Role in Climate (CORC) observations, along with most other observations of the tropical Pacific. Such a framework will provide a unique tool to understand the variability of the tropical Pacific in greater detail than has been possible before.

Over the course of the earlier years, a 1/3° tropical Pacific model was configured and run using a variety of initial conditions and forcing sets. Comparisons to observations have shown promising model/data agreement, suggesting that the model is capable to be used for data assimilation. The ECCO assimilation system has been implemented and forcing fields, initial and boundary conditions were adjusted to bring the model into greater consistency with TOPEX sea surface height, Reynolds sea surface temperature, and Levitus temperature and salinity profiles over one-year period. Several innovations were required to make the assimilation work, including novel methods for adjusting the open boundaries and for removing extreme sensitivity from the adjoint of the model. Assimilation experiments were first performed to evaluate the system and to tune its parameters. Assimilation was able to significantly improve the overall model fit to the data.

In the current academic year, we first continued the evaluation of the assimilation system and studied its sensitivity to different configurations and setups. Once validated, several improvements were added to this system including:

- Development of a new package in the ECCO-MIT assimilation code to properly assimilate in situ data. In this package, the model solution is interpolated online at the data positions in a multiprocessors environment. Special care had to be taken to make this process compatible with the TAMC adjoint compiler.

- Most of the tropical Pacific data sets were processed, analyzed to remove bad quality data, and then sampled before assimilation. This includes TAO salinity, temperature, zonal and meridional velocities, TMI sea surface temperature, surface drifters, XBT-CTD-ARGO profiles, and Johnson currents analysis. QuickSCAT data were also sampled to constrain the adjusted wind stress.

- The assimilation of profile data revealed a crucial need for smoothed error covariance matrices for the adjusted variables in the 4D-VAR cost function. Following Bennett (2002), Laplacian operators were then used to provide approximations for Gaussian covariance matrices.

- All the ECCO assimilation system weights were re-estimated and new parameterizations schemes were also introduced.

This new assimilation system is now working routinely and after 20 iterations, the assimilation was able to improve model/data consistency for all assimilated data sets over 1 year. We are now evaluating this new system before extending the length of the assimilation period.

1. Education Initiatives Sponsored by the NOAA Office of Climate Observation

Diane Stanitski
NOAA/Office of Climate Observation

PROJECT SUMMARY

A. Adopt a Drifter Program (ADP)

The Adopt a Drifter Program (ADP) was established during December 2004 by the NOAA Office of Climate Observation (OCO) to enable teachers and their students at all levels of education to infuse ocean observing system data into their curriculum. The ADP promotes a partnership between a school from the United States and an international school where students from both schools mutually adopt a drifting buoy to be deployed from a ship at sea. An educational sticker from each school is adhered to the drifter before deployment and teachers and their students access drifter location, and sea surface temperature and/or sea surface pressure data from the drifter online. During FY 2005, six schools adopted drifting buoys.

B. Sponsor of NOAA Teacher at Sea

During FY 2005, the NOAA Office of Climate Observation sponsored one teacher to participate in the NOAA Teacher at Sea Program. The OCO supported the sponsored teacher's travel to and from the scientific research vessel in Chile where the ocean research was conducted. Additionally, the OCO provided a stipend to the teacher and supported a reception on Capitol Hill to honor the teacher's accomplishments and the school that was involved.

C. Climate Education Working Group

During FY 2005, Diane Stanitski, of the NOAA Office of Climate Observation, helped create and co-chair the new Climate Education Working Group for NOAA. This group was and is responsible for initiating new ideas for climate-related education materials within the Office of Global Programs as well as working with intra-agency and interagency education-focused groups. As an outcome of this Working Group, the Office of Global Programs and the NOAA Office of Education created a new Climate Education Fellowship.

FY2005 PROGRESS

A. Adopt a Drifter Program (ADP)

The NOAA Office of Climate Observation (OCO) established the Adopt a Drifter Program (ADP) in December 2004 for K-16 teachers from the United States along with international educators. The ADP invites one school from the United States to partner with one international school where they collaborate to mutually adopt a drifter to be deployed from a ship at sea. This program provides teachers with an educational opportunity to infuse ocean observing system data into their curriculum. A drifting buoy (drifter) is a floating ocean buoy equipped with meteorological and/or oceanographic sensing instruments linked to transmitting equipment where the observed data are sent to data collection centers. A global array of 1250 drifting buoys was completed in September 2005 with the official launch of the 1250th buoy during the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) II conference in Halifax, Nova Scotia. The location of the 1250 buoy and all other adopted buoys as well as the near real-time sea surface temperature (SST) and sea surface pressure (SSP) data collected on the buoys can be monitored on the Adopt a Drifter Tracking Page at http://osmc.noaa.gov/OSMC/adopt_a_drifter.html. The ADP is run through the OCO with assistance from Kevin O'Brien at the Pacific Marine Environmental Laboratory (PMEL) in Seattle who maintains the Adopt a Drifter Tracking Page where students access data online from the adopted drifter. Craig Engler and Mayra Pazos, of the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, FL, coordinate the deployment of drifting buoys and the assignment of a WMO ID number for each school's adopted buoy.

Teachers develop lesson plans to encourage their students to analyze the drifting buoy data and apply it to help understand real-world systems. Students in the teachers' classes receive a drifter tracking chart to plot the coordinates of the drifter as it moves freely in the surface ocean currents. This enables teachers and students to more easily make connections between the data accessed on line and other maps showing oceanic and atmospheric circulation. During FY 2005, six schools adopted drifting buoys including San Marcos Middle School, California; Escuela de America, Chile; Southside Middle School, Arkansas; Greenbrier Middle

School, Virginia; Congressional School, Virginia; and Elsies River High School, South Africa.

B. Sponsor of NOAA Teacher at Sea

During FY 2005, OCO sponsored Mary Cook, an 8th grade science teacher from Southside Middle School in Batesville, Arkansas, to participate in the NOAA Teacher at Sea Program. Mary Cook (on right in Figure 1) participated in the deployment of a STRATUS buoy and tsunami buoy during a December 2004 cruise off the coast of Chile. She also wrote daily logs, interviewed scientists, took digital pictures, answered email from her students, and became the first teacher to participate in the Adopt a Drifter Program as part of her NOAA Teacher at Sea adventure. She boarded the BROWN on December 5 and departed from southern Chile in mid-January.

Mary Cook, the first teacher to adopt a drifting buoy, completed five lesson plans in conjunction with her trip on board the NOAA research vessel, RONALD H. BROWN. Her lessons involve simulating ocean surface currents, determining how ocean currents influence climate in coastal areas, tracking and mapping drifting buoys, comparing sea surface temperatures in different ocean basins, and ground-truthing satellite imagery with drifting buoy data. Her eighth grade students played a vital role in the development of her lesson plans and provided input based on their experiences tracking "Bob", their drifter's nickname, and using the ADP tracking web site to understand Bob's movement and the sea surface temperatures measured.

While on board the RONALD H. BROWN, Mary co-authored a children's science book with Diane Stanitski, of the OCO, written to describe Mary's experiences deploying the first adopted drifting buoy in the Pacific Ocean and to illustrate the global ocean observing system for climate. The book, entitled *Teacher at Sea: Miss Cook's Voyage on the RONALD H. BROWN*, emphasizes the scientific work conducted on board. OCO sponsored a reception for Mary on Capitol Hill to highlight her accomplishments. NOAA published the children's science book and complimentary copies are available by contacting Jennifer Hammond at jennifer.hammond@noaa.gov.

Figure 1. Mary Cook (Southside Middle School, AK teacher) and Jeff Lord (WHOI) deploy an adopted drifting buoy from the NOAA ship, RONALD H. BROWN, in December 2004.

CHAPTER 4

SATELLITE CONTRIBUTIONS TO THE OCEAN OBSERVING SYSTEM FOR CLIMATE

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Introduction

A recent workshop report begins with the sobering statement, “Measuring the small changes associated with long-term global climate change from space is a daunting task.” (Ohring et al., 2004) However, with over three decades of satellite-based measurements and continued improvements to the quality and availability of these observations, there is now more reason than ever to expect satellites to fill a critical and unique role in the global ocean observing system for climate. Satellites, with their ability to make global observations on a frequent basis, provide a dimension to the ocean climate observing system that would be impractical or impossible to achieve with in situ platforms alone. These frequent, global observations are in many cases made at very fine spatial resolutions, enabling many new climate-ecosystem interaction studies as well as enhancing traditional climate science.

Making effective use of satellites as climate platforms requires overcoming several technical and scientific challenges. For example, numerous Advanced Very High Resolution Radiometers (AVHRRs) have flown on board the series of NOAA polar orbiting satellites for more than 20 years. Despite the similarities of the sensors, each behaves differently and each rides on a satellite whose characteristics differ from the others in the series. Adding to this challenge, both the instrument responses and the platform characteristics can and do change over time. Additionally, to detect typically small climate signals, climate-quality algorithms must be developed iteratively, continually improving over operational, near real time algorithms. All of these challenges must be overcome if a credible, consistent record is to be generated.

In addition to the scientific and technical challenges, several organizational difficulties must also be resolved. Generating *climate data records* (CDRs), defined as a time series of sufficient length, consistency, and continuity to determine climate variability (NRC, 2004), requires a sustained, ongoing commitment to regularly reprocess the entire satellite time series using the latest available algorithms and techniques. Steps must be taken to insure guidance and feedback from the community is incorporated in the CDR generation process. To generate the best possible CDRs, data may be required from satellites operated by different agencies or countries requiring a high level of national and international coordination. These and other organizational and institutional challenges must be met to insure optimal satellite contributions to the ocean observing system for climate.

In addition to meeting these challenges, environmental observations from satellites must always be viewed as fundamentally integrated with and dependent on in situ measurements if their value is to be fully realized. All satellite observations require in situ measurements in algorithm development, quality control, instrument characterization, and validation. Neither in situ nor satellite based observations can be relied on alone if a full understanding of the complex climate system is to be achieved. One example of the tight connection between in situ and satellite platforms is the Marine Optical Buoy (MOBY), which supports the in situ validation of satellite ocean color estimates from space. Another area where satellites and in situ measurements work together to observe climate change is the determination of sea level rise, where both satellite altimeters and in situ tide gauge networks are used. Satellite reprocessing efforts such as the Pathfinder project discussed below, which work to produce longer, more consistent and accurate data streams, rely heavily on large numbers of moored and drifting in situ buoys to calculate algorithm coefficients and conduct validation studies. In some areas, such as the determination of sea ice trends, gaps in the satellite record can only be filled by in situ observations of sea ice concentration. These examples and many more point to the need to maintain both satellite and in situ observing and reprocessing capabilities.

Satellite based observations of the oceans have already begun contributing to the climate observing system in many areas. Five of these areas are sea surface temperature (SST), ocean color, marine winds, sea surface topography, and sea ice. For each of these areas, a brief discussion of the importance of that parameter class to climate monitoring will be given along with a brief history and current status of the space-based sensors used to measure that parameter. Some example satellite products currently used will also be given along with a look forward into the future of measuring these parameters from space.

Sea Surface Temperature

Why Observe SST?

Of the many oceanographic parameters capable of being observed from space, SST is perhaps the single most important for climate monitoring. Satellite observations of SST variability and trends can be made at the global, regional, and even local level. These observations are used to measure the magnitude of ocean surface temperatures changes, initialize and validate numerical models, and understand the role of thermal stresses on marine ecosystems. An enormous diversity of applications and research studies rely on this critical parameter.

A Brief History

High quality infrared-based SST measurements have been made continuously since late 1981 when the five-channel AVHRR on the NOAA-7 polar orbiting satellite became available, but earlier attempts date back to 1972. The AVHRRs have now flown on 12 NOAA polar orbiters and provide the longest continuous time series of any satellite-based oceanographic parameter. Numerous other satellite sensors have also used infrared measurements to determine SST. In 1991, the European Space Agency launched the Along Track Scanning Radiometer (ATSR-1), followed by the ATSR-2 in 1995 and an improved version known as the Advanced-ATSR (AATSR) in 2002. These sensors employ a dual-view of the ocean surface, thereby permitting a highly accurate accounting of the errors introduced by the atmosphere. Geostationary satellite observations of SST are available from late 2000, using the NOAA Geostationary Operational Environmental Satellites (GOES), allowing repeated views of the ocean surface multiple times per day. In late 1999, NASA launched the first Moderate-resolution Imaging Spectroradiometer (MODIS) on board its Terra platform, and a second one on Aqua in 2002. Microwave observations, which have an important advantage in being largely unaffected by clouds and intervening atmosphere, have also been used to determine SST. The Tropical Rainfall Measuring Mission (TRMM) and its TRMM Microwave Imager (TMI) provide SSTs back to December of 1997. The Advanced Microwave Scanning Radiometer-EOS (AMSR-E), on board NASA's Aqua platform, also takes advantage of the nearly all-weather capability of the microwave portion of the spectrum. These observations are made at substantially coarser spatial resolutions than the infrared measurements to overcome the low microwave signal to noise ratio.

Present Status and a Look Forward

Currently, both MODIS sensors continue to function and the AVHRRs on board NOAA-17 and NOAA-18 are in operational status. GOES platforms continue to deliver SST measurements, as does the AATSR, TMI, and AMSR-E. Other platforms are also currently making SST observations. In the next several years, as part of the next generation National Polar-orbiting Operational Satellite System (NPOESS), the Conical-scanning Microwave Imager/Sounder (CMIS) and the Visible-Infrared Imager-Radiometer Suite (VIIRS) will carry on the time series established by the microwave platforms, the AVHRRs, and the MODIS sensors. Another AVHRR will also be on launched in 2006 on board the European MetOp platform and on the final in the series of current NOAA polar orbiters, carrying the SST observations from AVHRR forward several more years.

Critical Activities

This variety of SST observations from space highlights priority areas in SST science and CDR development activities: consistently reprocessing individual sensor observations, combining multiple contemporaneous observations from different sensors, and merging time series from individual sensors into a consistent record. Accomplishing these tasks to produce climate quality products requires, among many other things, a sophisticated understanding of diurnal variability to account for the different observation times of the various platforms and a quantitative determination of single-sensor uncertainties and biases between the different sensors and between the satellites and in situ observations, so they can all be effectively combined.

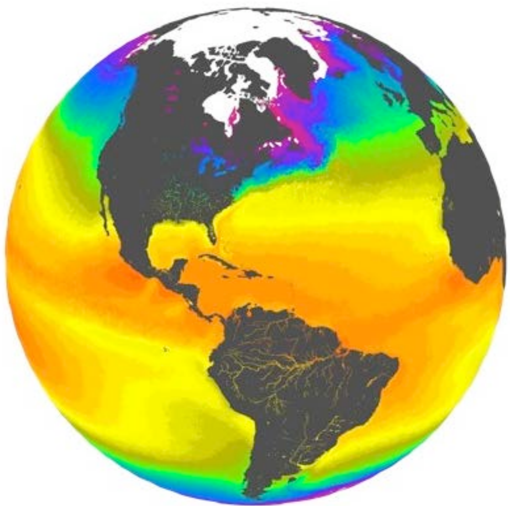

Figure 1: Climatological week 50 from 1985-2001 Pathfinder Version 5 SST data, with ice mask from w eek 50 of 2003. Developed using methods of Casey and Cornillon (1999).

Many of these issues are being addressed at both the national and international level. For example, NOAA's National Oceanographic Data Center, along with contributions from the NOAA Coral Reef Conservation Program, supported the AVHRR Pathfinder effort for the last four years (funding has expired and is now being sought to continue the project). Pathfinder is a single-sensor series reprocessing effort focused on creating global SST CDRs from the AVHRRs on the NOAA polar orbiters (http://pathfinder.nodc.noaa.gov). The Pathfinder project resulted in a global, 4 km resolution time series spanning 1985-2005 on multiple averaging periods (daily, 5-day, 7-day, 8-day, monthly, and yearly) with corresponding climatologies (Figure 1). The need for reprocessing efforts like this is clearly demonstrated in Figure 2, which illustrates the difference in SST trends between 1985 and 2004 determined using operational AVHRR SST data and Pathfinder AVHRR data. Taking the difference clearly highlights large regions of the global ocean where the trends differ by more than 0.1°C/year. These differences are as large as the observed trends during this period (note that globally averaged trends over the last 100 years are much smaller, on the order of 0.1°C/decade) and in some cases indicate regions where the sign of the trends are reversed relative to one another.

With a focus on other sensors, the commercial research company Remote Sensing Systems routinely conducts reprocessing of the TMI and AMSR-E SST products (http://www.remss.com). The European SST community has recently decided to begin a reprocessing of the entire ATSR and AATSR time series and NOAA's Office of Research and Applications works continually on improving SST estimates from the GOES platforms. These projects focus on observations from a single class of satellite sensor, while the international GODAE High Resolution SST project works to combine SST observations in both real time (http://www.ghrsst-pp.org) and in delayed mode for higher accuracy, climate quality products (http://ghrsst.nodc.noaa.gov).

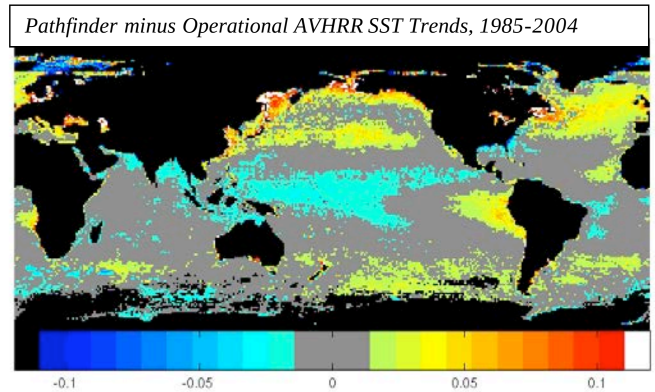

Figure 2: Pathfinder linear SST trends for 1985-2004 minus the corresponding Operational AVHRR linear trends. Trends are calculated on a weekly, one-degree grid. The trend differences are indicated in °C/year. Grey areas are where the differences are small (plus or minus 0.01 °C/year). Warm (cool) hues indicate areas where the Pathfinder trend is more (less) positive than the Operational AVHRR trend.

Ocean Color

Why Observe Ocean Color?

Satellite measurements of visible and reflected near infrared light result in the suite of products termed "ocean color". The color of the ocean varies as a result of variations in three primary factors: phytoplankton and algae, suspended inorganic sediment, and both dissolved and particulate detrital pigments. The patterns and variations in these three groups both result from impacts of climate and may also influence climate. A potential feedback between the ocean biology and the climate system involves carbon budgets. Phytoplankton fix carbon, but the timing and intensity of ocean blooms depends on climatic factors, such as upwelling, runoff, and mixing of the ocean. Detrital pigments transport carbon from land to the ocean, and can lead to loss of carbon to the ocean floor. Ocean color data from satellites help in identifying the magnitude of these processes.

A Brief History

The ocean is much darker than land and the atmosphere, so remote sensing of ocean color is more difficult than land features. However, ocean color from space started with Landsat-1, launched in 1972. The first Landsat series, with the Multispectral spectrometer (MSS) had bands that measured green, red, and reflected near-infrared light with a nominal pixel size of 80 m, and a repeat of every 18 days. While this sensor was not intended for ocean applications, it was found useful in identifying turbidity patterns in estuaries. With Landsat-4, launched in 1982, the Thematic Mapper was added. This sensor added a blue band and increased the resolution to 30 m. It has proved useful in examining structure of coral reefs, as well as seeing patterns of river plumes. The AVHRR, operating at a relatively coarse 1 km resolution, is another sensor that provides information on ocean color, although it had never been designed to do so. However, AVHRRs enable near-real time monitoring by providing observations every day, limited only by clouds.

The first sensor designed specifically for ocean color observations was the Coastal Zone Color Scanner (CZCS), launched in November 1978 on the Nimbus-7 satellite. It was about ten-fold more sensitive than Landsat, and could collect data every few days, with a ground pixel size of about 800 m. The CZCS provided an extraordinary data set for the first three years, and continued operating until 1986. The CZCS has been used extensively to estimate phytoplankton biomass and primary productivity over large regions of the ocean. Despite the value of CZCS, it was 10 years before other sources of ocean-color data were launched, with the Moderate Optoelectrical Scanner (MOS), the Ocean Color and Temperature Scanner (OCTS), and the POLarization and Directionality of the Earth's Reflectances (POLDER) instrument.

In 1997, with the launch of the Sea-viewing Wide Field of View Sensor (SeaWiFS) on the commercial satellite OrbView-2, came the first ocean color mission with a goal of routinely and continuously characterizing global ocean color. SeaWiFS was configured to collected data at 1-km in a local mode, but also to collect data globally at 4 km resolution making it the first satellite specifically designed to routinely collect ocean color data for the world ocean. (http://oceancolor.gsfc.nasa.gov). It provides details on both global and local scales to highlight individual events as well as seasonal to interannual variability, including such global phenomenon as the ENSO impacts on biomass in the ocean. A climatology created using SeaWiFS data between 1998 and 2003 is shown in Figure 3. The MODIS sensor, with bands similar to SeaWiFS, also determines ocean color and was launched on NASA's Terra satellite in late1999 and on Aqua in 2002.

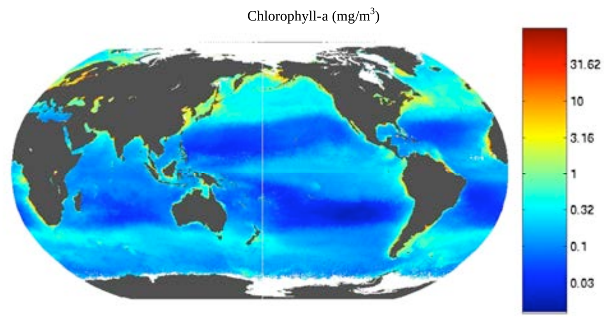

Figure 3: Chlorophyll-a climatology for April based on SeaWiFS v4 data from 1998-2003.

Current Status and a Look Forward

As of early 2006, SeaWiFS is still operating and producing high quality data. Since SeaWiFS is commercially owned, availability of SeaWiFS depends on purchasing licenses. Currently NOAA and NASA have covered global licenses to the end of 2006. Ocean color observations from MODIS on Aqua have been fully calibrated and now provide global data of a quality comparable to SeaWiFS (http://oceancolor.gsfc.nasa.gov). The sensor is the prototype for the VIIRS instrument that will fly on the next generation NPOESS environmental satellites, starting about 2009 with the launch of the NPOESS Preparatory Project spracecraft. For a list of other sensors providing ocean color data of various resolutions and quality, see the International Ocean Colour Coordinating Group (IOCCG) website (http://ioccg.org).

Critical Activities

Development and application efforts are underway in many parts of the world, with the IOCCG sponsoring many working groups focused on items like ocean color algorithms, sensor calibration, and the merging of ocean color data from multiple sensors. Implementing these activities and applying them consistently over the ocean color time series is critical in developing CDRs for these important parameters.

Ocean Surface Topography

Why Observe Ocean Surface Topography?

Space-borne altimeters provide long-term global measurements of the ocean's surface topography. In a dynamical sense, sea surface height measurements are analogous to the surface atmospheric pressure measurements used in numerical weather models. Large-scale ocean surface currents are in geostrophic balance with the slope of the sea surface. For inter-annual to decadal time scale phenomena, such El Nino/Southern Oscillation and the North Atlantic Oscillation, these measurements provide a uniquely valuable way of monitoring circulation and heat content changes of the upper ocean associated with changes in sea surface height.

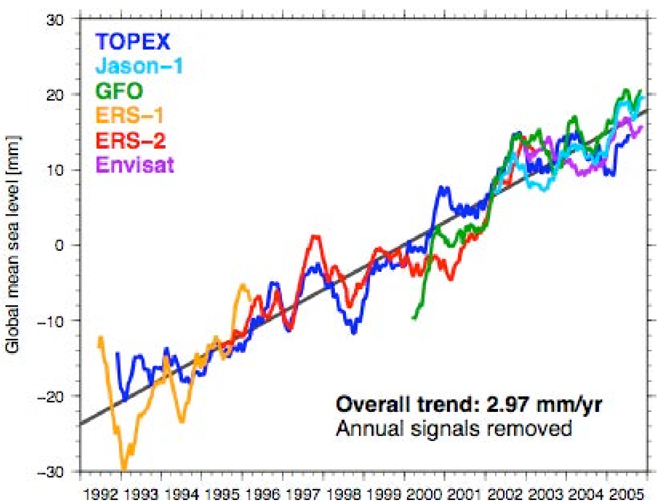

Figure 4: Global mean sea level determined by TOPEX, Jason-1, Geosat-Follow-On (GFO), ERS-1, ERS-2, and Envisat radar altimeters

On time scales greater than a decade, the near global coverage provided by satellite altimeters makes it possible to estimate global sea level rise. By paying careful attention to instrumental and environmental (e.g. path delay) corrections normally applied to an altimeter's range measurement, it is possible to construct a consistent record of global mean sea level change from six different altimeter missions over the past fourteen years. As shown in Figure 4, the overall trend for this interval is 2.97 mm/year, roughly 50% greater than the ~2.0 mm/year rate of rise observed over the past century from tide gauge measurements (Scharroo et al., 2006). Whether this rate increase reflects a true long-term change or simply decadal variability is presently unknown. Regional variations in sea level trends around the globe are shown in Figure 5.

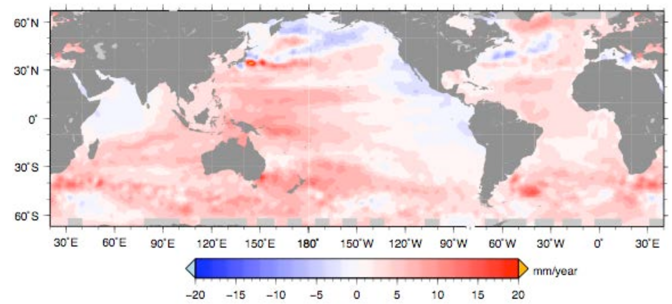

Figure 5: Regional sea level trends over Jan 1993 - Feb 2006 from TOPEX and Jason-1 satellite altimeter observations. The global mean of this map is the same as the six-altimeter solution shown in Figure 4.

A Brief History

Radar altimetry from space began in the late 1970s with the GEOS-3 and SeaSat missions, but the first useful altimeter for the climate record, both in terms of measurement accuracy and record length, was the U.S. Navy's Geosat mission (1985-1989). Unfortunately there is a 2 year gap between Geosat and the next subsequent mission, the European Space Agency's ERS-1 beginning in 1991, which prevents a cross-calibration between the missions. ERS-1 and the launch of the NASA/CNES Topex/Poseidon mission in 1992 began the uninterrupted altimetric record that continues up to the present. Topex/Poseidon provided data until October 2005, yielding an unprecedented 13-year record of high accuracy sea surface height data.

Current Status and a Look Forward

Currently there are three fully functional satellite radar altimeters, each flying in a different orbital configuration: Jason-1, the successor to Topex/Poseidon (10-day repeat period, 66° inclination); Geosat Follow-on, the successor to Geosat (17-day repeat period, 108° inclination); and Envisat, the successor to ERS-1 & ERS-2 (35-day repeat period, 98° inclination). Ocean surface topography data from these sensors is now widely available (see for example http://podaac.jpl.nasa.gov/ost and http://www.aviso.oceanobs.com/html/donnees/welcome_uk.html). Because altimeters provide height measurements only at the nadir location along their ground track (and not a 'swath' of data, as is typical of other satellite instruments) there is always a trade-off between spatial and temporal resolution. Fortunately, for the large-scale processes generally of interest for climate observations, a single high-accuracy altimetry mission such as Topex/Poseidon and Jason-1 is sufficient. The next such mission will be Jason-2/OSTM (Ocean Surface Topography

Mission), which is scheduled for launch in mid-2008 and will replace Jason-1 to continue the long time series begun by Topex/Poseidon. Shorter space and time-scale phenomena at the ocean's mesoscale are not adequately sampled by a single altimeter, but the present configuration of three complementary altimeters does capture most of the signals of interest. Applications such as ocean eddy monitoring, surface current analyses, and ocean heat content for hurricane intensity forecasting require this higher resolution sampling (see http://ibis.grdl.noaa.gov/SAT for more information on altimetry research and applications). In the next few years, however, it is likely that Geosat Follow-On and Envisat will cease without replacement, and there will only be one operational altimeter – Jason-2/OSTM.

Critical Activities

To insure the accuracy and value of altimeter observations for climate studies, particularly for the global sea level rise problem, it is important to have a period of overlap between satellite missions. Only by directly comparing the average heights between missions is it possible to accurately detect and correct for offsets and thereby extend the global sea level record over multiple decades. An overlap is also useful for identifying subtle instrument dependent problems, such as a drift in one of the environmental corrections to the range measurements. A problem of this type was detected in the Jason-1 microwave radiometer measurements, during the 4-year overlap between the Jason-1 and Topex/Poseidon missions. A method of compensating for this drift has now been put into place.

The value of satellite altimeter observations for climate studies is also greatly enhanced by the operation of two in situ ocean observing systems supported by the NOAA Office of Global Programs (OGP): a global network of GPS-controlled tide gauge stations, and the ARGO profiling drifter array. Relative sea level observations from more than 80 tide gauge stations are currently providing an independent, ground-based check on the stability of each satellite altimeter mission. Routine comparisons between gauge and altimeter measurements show that altimeter-measured trends are accurate within +/-0.4 mm/year. Thus, the 2.97 mm/year trend observed over the past decade by satellite altimetry (Figure 4) is significantly higher than the gauge-measured trend over the past century.

The ARGO profiling system provides an important, complementary set of climate observations: global measurements of the vertical density structure of the ocean. An altimeter measures sea surface height, which is a function of the both the mass and vertical density structure of the ocean at a given location. By combining these two data sets, one can obtain a complete description of the state of the ocean, the holy grail of ocean climate monitoring. One problem that may soon become accessible through the combination of these two data sets is that of determining how much of global sea level rise is due to thermal expansion versus the addition of new water to the oceans due to the melting of continental ice.

Ocean Surface Winds

Why Observe Ocean Surface Winds?

The observation of marine winds from space-borne instruments provides a global measure of the fluid dynamics in the lower atmosphere where the impact of climate is felt most directly. Such observations lead directly to the ability to track and understand significant environmental events, such as tropical storms, and to monitor their intensity variations. From a more inclusive perspective, marine winds are the dynamic coupling link between the ocean and the atmosphere, providing fundamental information for understanding the energy and momentum exchanges across the air/sea boundary. A consistent, long term, and global record of these winds is fundamental for monitoring and modeling climatological phenomena.

A Brief History

The satellite instruments that measure ocean surface winds fall into three types: microwave radiometers, scatterometers, and synthetic aperture radars (SAR). The first two have reached advanced levels where CDRs can be generated with global coverage, while SAR is generally used to measure specific, isolated environmental events.

Microwave radiometers are particularly well quantified, the most historically notable being the Special Sensor Microwave Imager (SSM/I). Since 1987 the Defense Meteorological Satellite Program (DMSP) has flown this instrument on a series of satellites and presently has three functioning operationally that provide full global ocean surface wind speed coverage in less than 24 hours. In 2003 the Special Sensor Microwave Imager Sounder (SSMIS), the next generation of SSM/I, was launched and presently has data available. Other advanced radiometers capable of measuring ocean surface wind speed include the TMI and the AMSR-E, which also provide contemporaneous measurements of SST as discussed earlier. Among the most unique instruments to have been recently placed in orbit, however, is WindSat on the Coriolis satellite in January of 2003. WindSat uses polarimetric capabilities to resolve the full ocean surface wind vector including both speed and direction.

SKYLAB operated the first scatterometer in space, the S-193, in 1973 and 1974, demonstrating the feasibility of using scatterometers to measure ocean surface winds. The SeaSat-A Satellite Scatterometer (SASS) onboard the SeaSat oceanographic satellite followed in 1978. Although SASS operated for only 100 days, the data obtained was successfully used to generate accurate ocean surface wind velocity measurements. The European Space Agency (ESA) successfully demonstrated the operational advantages of scatterometers with their ERS-1 and ERS-2 satellites, launched in 1991 and 1995 respectively.

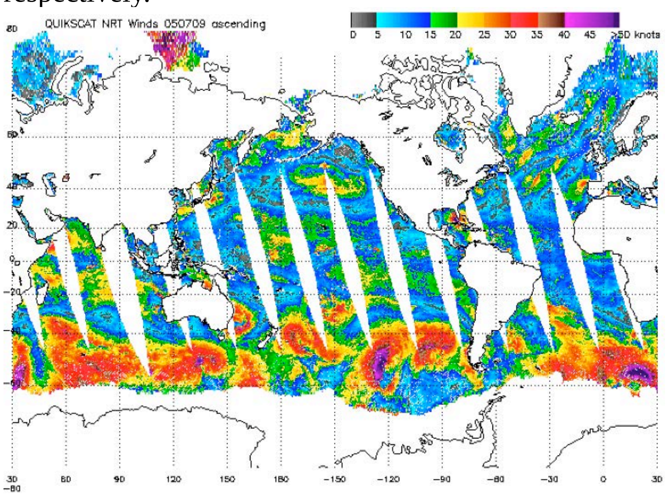

Figure 6: Global QuikSCAT Winds showing single day coverage by ascending pass.

NASA launched its NASA Scatterometer (NSCAT) aboard the ADEOS satellite in 1996. NSCAT operated flawlessly for 9 months, providing data for the production of ocean surface wind vector fields with a 25 km spatial resolution, before suffering a catastrophic power failure on May 9, 1997.

To minimize the temporal data gap, NASA put forth the Quick Scatterometer (QuikSCAT) mission to place and maintain a scatterometer in orbit until the launch of ADEOS II (see Figure 6 for plot of daily coverage by QuikSCAT). A SeaWinds scatterometer was used on the QuikSCAT satellite, which was launched in July of 1999 and has been operational since. The QuikSCAT mission proved to be not only a scientific and operational success, but absolutely invaluable to the remote sensing community as ADEOS II failed roughly 9 months after it became operational in October of 2003.

Current Status and a Look Forward

Although NSCAT on ADEOS and SeaWinds on ADEOS II operated for 18 months, QuikSCAT has provided almost seven years of continuous data and presently carries the only microwave scatterometer capable of global ocean surface wind measurements. The Advanced Scatterometer Instrument (ASCAT) of the European Space Agency's MetOp mission offers the most immediate plan for another wind measuring scatterometer in space. WindSat continues to produce high quality wind fields of comparable resolution to QuikSCAT, but is still fundamentally part of a scientific proof-of-concept mission. The CMIS, part of the NPOESS instrument collection to launch around 2010, is a future polarimetric radiometer designed to operate on similar principals as WindSat.

Critical Activities

The remarkable duration of the QuikSCAT mission has brought satellite measurement of ocean wind fields into the realm of climate science, allowing CDR production to be routine in a weekly and monthly temporal basis, such as the weekly and monthly QuikSCAT global wind fields created by Remote Sensing Systems. Previous to QuikSCAT, the measured global ocean surface wind vector field was scattered temporally and spatially at best, with ERS-1 and ERS-2 offering globally distributed measurements, but with a narrow swath. QuikSCAT is approaching an unprecedented seven years of continual operations, but has no reliable U.S based replacement set to compliment or continue this record production. A wind speed climatology for the month of April is shown in Figure 7, based on 1999-

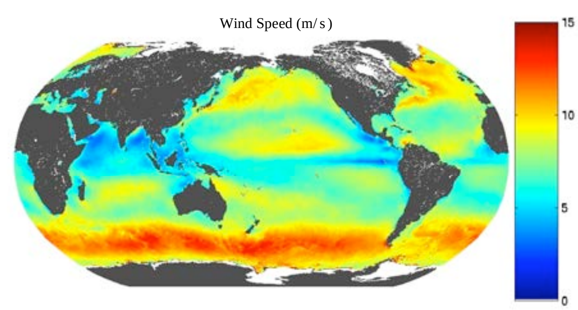

Figure 7: QuikSCAT Winds speed climatology for April, from 1999-2004 data. See http://data.nodc.noaa.gov/pathfinder/NODC_QuikSCAT_Winds for more information.

2004 QuikSCAT data. A meaningful CDR wind field obviously requires a reasonably unbroken data flow. The ASCAT instrument on the first of the MetOp satellites, to be launched in 2006, will do much to compliment the present ocean wind field climate record and prevent a gap in the data flow. Also of significance is the cross-validation of different surface wind measuring platforms, such as the C-band ASCAT scatterometer, the Ku-band SeaWinds scatterometer, and more varied instruments such as the polarimetric radiometer WindSat. Included in this is more sophisticated validation of measurements of extreme environmental events, such as tropical storms and hurricanes, with more localized measurements using similar scatterometers and radiometers aboard NOAA WP-3D aircraft. As the remote sensing community is still in a learning phase for using passive polarimetric techniques, such studies and validation are crucial for understanding the cross-calibration/validation issues of wind measuring scatterometers and radiometers and how to exploit the benefits of both instrument types for a more complete marine wind field climate record.

Sea Ice

Why Observe Sea Ice?

Most climate models predict polar amplification of warming – that is, polar regions experience climate change sooner and more intensely than mid latitudes. For this reason scientists have long been interested in monitoring sea ice as a climate indicator. From a climate perspective, Arctic sea ice is more interesting since it plays a greater role in oceanic and atmospheric circulation than Antarctic sea ice, which also occupies only a relatively small area south of 75° South.

Over time, warming reduces the volume of sea ice. Thinner sea ice, or ice covering less area, modifies climate by insulating the atmosphere from the ocean less. In winter's polar night, breaks in the sea ice cover release heat and moisture to the atmosphere; in summer's continuous daylight, reductions in ice concentration (the percentage of an area covered by ice floes) enhance heat flux from solar radiation into the ocean. Sea ice, like snow, is a high albedo surface that reflects incoming solar radiation. Sea water, by contrast, is dark and absorbs much more radiation. Modeling ice-albedo feedback (where less ice leads to more heat absorption in the ocean which leads to less ice, and so on) is a critical aspect of General Circulation Models (climate models).

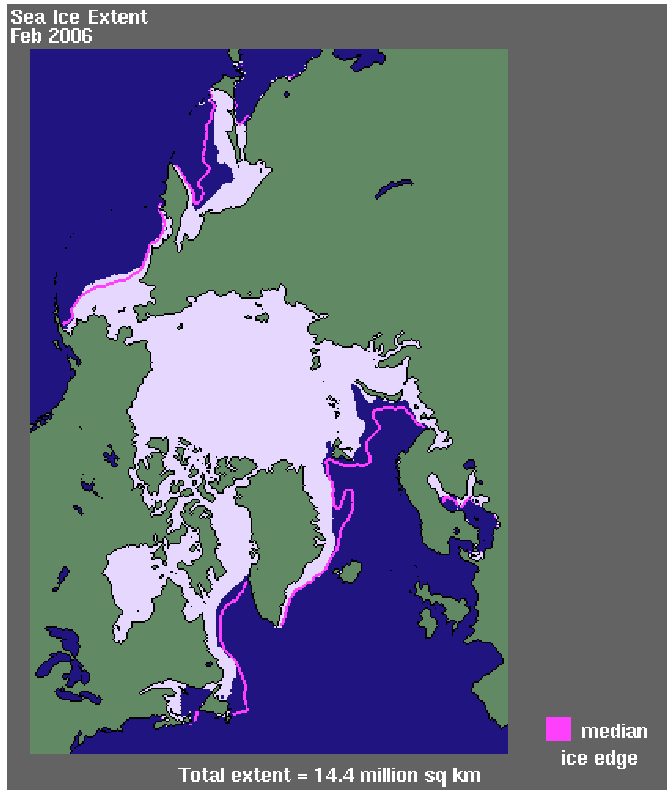

*Figure 8: Sea ice extent for February shown with the climatological (1979-2000) median extent. The characteristic Odden shape appears in the median north of Iceland and east of Greenland. Extent anomaly image from the Sea Ice Index (**http://nsidc.org/data/seaice_index**).*

Sea ice has a role in oceanic circulation, the "conveyer belt" of heat transport, as well. As new ice grows, it releases brine into the upper layer of the ocean and increases the density of the water. Under the right conditions, cold, super dense water forms and sinks below the mixed layer to great depths, serving as a driver for thermohaline circulation. The Odden (Norwegian for headland), a tongue of ice that sporadically forms off the east Greenland ice edge in winter, is associated with this type of deep water convection. Although recent work has shown that an Odden event is not a requirement for deep water convection, the reduction, since the 1980s, in the frequency with which the Odden appears has caused concern (Figure 8).

A Brief History

Sea ice and ocean water have dramatically different electromagnetic signatures in microwave, infrared, and visible-band data, making satellite imagery of sea ice relatively straightforward to interpret. Operational ice services use satellite data from variety of sources to manually construct analyses. Passive microwave data have proven most useful for climate data records, since ice concentration estimates are not affected by cloud cover and the polar night, and more than 30 years of data are now available. The single channel Electrically Scanning Microwave Radiometer (ESMR) launched on Nimbus-5 in 1972; the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 provided data from 1978 until 1987; the time series from the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (DMSP SSM/I) sensors began in 1987 and is ongoing; and the future NPOESS CMIS instrument is intended to continue the record.

Most sea ice data sets are based on algorithms that had their genesis with NASA investigators. Data sets from two algorithms, the NASA Team (NT) and the Bootstrap (BT), are mature and widely used. Time series of sea ice extent (total ocean area containing at least 15% ice) sea ice area (total area covered by ice) and sea ice concentration (percentage area covered by ice) are available from the National Snow and Ice Data Center (NSIDC) on a 25 km grid (for a summary of these and other Sea Ice Products at NSIDC see http://nsidc.org/data/seaice). The NT and BS algorithms use the dual polarization 19.3 (or 18.0 in the case of SMMR) and 37.0 GHz channels. A considerable amount of work has gone into making records consistent across changes in instrumentation and platform. For example, the 1.3 GHz difference between SMMR 18.0 and SSM/I 19.3 channels results in a discontinuity in the data record of raw brightness temperatures, and a greater sensitivity to weather effects in the SSM/I data. Differences are notable even between SSM/I instruments. Only recently has the gap between the single channel ESMR, which operated until 1977, and SMMR, which began in 1978, been bridged, using ancillary data in the form of operational analyses from the National Ice Center.

Current Status and a Look Forward

Sea ice is highly variable, so deriving trends with confidence demands long records in which consistency may be more important than accuracy. For example, ice concentration from passive microwave tends to be biased low by a seasonally dependent amount, with underestimation greatest in summer, when pools of melt water, indistinguishable from ocean water to the sensor, form on the surface of the ice. Sea ice extent is less affected than is ice area, making extent a more robust indicator. The BT and NT algorithms take different approaches and yield different results, but the key characteristic of data sets from both algorithms relevant to climate data records is that they are internally consistent, with consistent biases, across changes in instrumentation. The NSIDC Sea Ice Index uses the combined SMMR-SSM/I record and NT algorithm to show trends (Figure 9) and anomalies on a monthly basis.

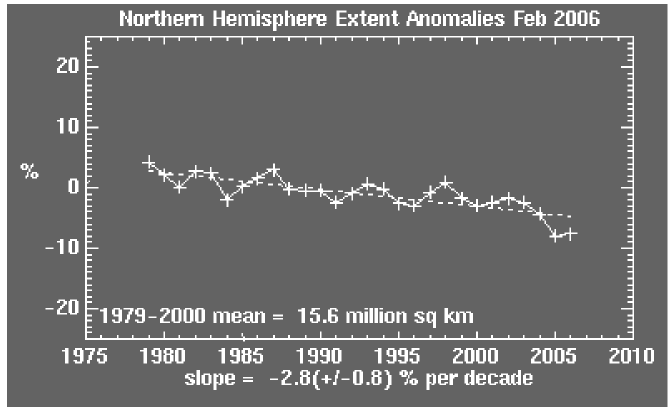

Figure 9: Extent anomaly trend for February from the Sea Ice Index (http://nsidc.org/data/seaice_index). Trends for the Southern Hemisphere are also available.

New instruments and algorithms offer hope for better accuracy. The NPOESS CMIS, like the AMSR-E now in orbit on NASA's Aqua platform, will have an 18.7 GHz channel that is optimal for reducing weather effects. AMSR-E has a resolution that is about twice that of SSM/I, and the CMIS resolution will be slightly better than that of AMSR-E. This finer spatial resolution alone improves the accuracy of concentration and extent. An algorithm called NT2 uses the higher frequency channels available on SSM/I and later sensors to overcome weather and snow effects, and is being used with AMSR-E data.

Satellite records alone give only a two dimensional view of ice, but what is most useful is sea ice volume. Obtaining ice freeboard from satellite altimetry for estimates of ice thickness is a promising technique, but for now in situ instrumentation is depended on for ice thickness. However, after the record 2005 minimum in ice extent, confidence is growing that the decline in ice extent reflects a significant loss in ice volume as well (see Sea Ice Decline Intensifies at http://nsidc.org/news/press/20050928_trendscontinue.html; a joint NSIDC, NASA, and University of Washington press release).

Critical Activities

In the past, NOAA/NASA Polar Pathfinder funding was crucial to the development of the SMMR-SSM/I time series. A similar effort is needed to extend SSM/I with CMIS, and should include research with AMSR-E to prototype CMIS ice products. NPOESS is not planned for launch until years after the Aqua design life ends in 2008, likely leaving a gap between AMSR-E and CMIS coverage. DMSP should cover this gap, but the operational nature of the DMSP program has meant that overlaps between sensors have been short. The intercalibration of SMMR and SSM/I ice records is based on only a six-week overlap period in 1987 when both sensors operated. Short overlap times impinge CDR quality; an overlap of at least 1.5 years (covering all seasons in both hemispheres) provides substantially better capability to account for sensor differences.

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APPENDIX A

Recent Publications

Reviewed Publications and Articles in Press

Ando K., T. Matsumoto, T. Nagahama, I. Ueki, Y. Takatsuki, and Y. Kuroda, 2005: Drift characteristics of a moored conductivity-temperature sensor and correction of salinity data. *J. Atmos. Oceanic Technol., 22*, 282-291.

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The Ocean in a High CO_2 World: http://ioc.unesco.org/ioccp/HighCO2World.htm

APPENDIX B

Professional Development and Community Service by Scientists Funded by the NOAA Office of Climate Observation

1. Community Service (e.g., appointments to science and implementation panels)

Molly Baringer (NOAA/AOML)
AGU Ocean Science Secretary; Member NOAA/OAR ship time scheduling panel.

Nicholas Bates (BBSR)
Committees: Scientific steering group member for the IOC-SOCR International Ocean Carbon Coordination Project (IOCCP); International Advisory Member of the European CarboOcean project; working group member for the SOLAS-IMBER carbon implementation plan; member for SOLAS-IMBER carbon working group on "Surface Observations".

Richard Bouchard (NOAA/NDBC)
Co-chaired and attended the Salinity Data Best Practices Workshop (August 2005, Charleston, SC).

Mark Bourassa (FSU)
NASA Ocean Vector Winds Science Team; NASA/OSU QuikSCAT mission; Next Vector Winds Mission Science Working Group; AMS Committee on Interaction of the Sea and Atmosphere; SEAFLUX organizing committee; NOAA OCO Ocean Observing System Team of Experts (with Smith)

John Bullister (NOAA/PMEL)
Affiliate Associate Professor, School of Oceanography, University of Washington; Fellow, Joint Institute for the Study of the Atmosphere and Ocean; "Decadal Changes in Dissolved CFCs in the Eastern Basin of the North Atlantic"; American Geophysical Union Meeting.

William Burnett (NOAA/NDBC)
NDBC DAC Director; represents NDBC on the DBCP and reported on NDBC/DAC activities at the annual DBCP workshop held in Chennai, India (October 2004); co-organizer and co-technical lead for the QARTOD II Workshop (March 2005, Norfolk, VA), focusing on real-time QA/QC of ocean temperature, salinity, current, and waves data; co-chaired and attended the Salinity Data Best Practices Workshop (August 2005, Charleston, SC).

Francisco Chavez (MBARI)
Member of NSF Geosciences Advisory committee (2003-2005); Member NSF Alan T. Waterman award committee (2003-2005); Member Advisory Board of the Instituto del Mar del Peru (IMARPE), the Peruvian fisheries and oceanography institute (2003-); Member Board of Directors of the Center for Integrated Marine Technologies (2002-); Member Board of Governors of Pacific Coastal Observing System (2003-); Member Science Team Global Ocean Timeseries (2002-); Member COCOA (Hyperspectral satellite coastal color imager) Science Team (2003-); Member of Governing Council for Central and Northern California Coastal Ocean Observing System (CeNCOOS) (2005-).

Don Conlee (NOAA/NDBC)
Co-organizer and co-technical lead for the QARTOD II Workshop (March 2005, Norfolk, VA), focusing on real-time QA/QC of ocean temperature, salinity, current, and waves data.

Steven Cook (NOAA/AOML)
WMO/IOC Data Buoy Cooperation Panel**;** WMO/IOC Ship Observations Team, Chairman – Ship of Opportunity Implementation Panel, Convener - Task Team on VOS Recruitment and Program Promotion, Task Team on VOS Automated Systems, Expert Group on Instrument Testing.

Meghan Cronin (NOAA/PMEL)
Co-Chair U.S. CLIVAR Process Study and

Model Improvement Panel, U.S. CLIVAR Summit, August 2005, Keystone, CO; Co-chair of "KESS and Beyond" science meeting at JAMSTEC, Yokohama, Japan, June 2005; Organizer of "Workshop on the Application of EPIC2001 Data for Testing and Improving Coupled Atmosphere-Ocean Models" at UW/APL in May 2005; Member of advisory panel for merging NOAA PACS and GAPP programs into CPPA program, 30 November 2004; Committee member for C. Jiang, M.Sc. granted December 2004, University of Washington.

Richard Crout (NOAA/NDBC)
Co-chaired and attended the Salinity Data Best Practices Workshop (August 2005, Charleston, SC).

Yeun-Ho Chong Daneshzadeh (NOAA/AOML)
Global Temperature Salinity Profile Program committee.

Craig Engler (NOAA/AOML)
WMO/IOC Data Buoy Cooperation Panel.

Richard Feely (NOAA/PMEL)
CLIVAR/CO_2 Repeat Hydrography Oversight Committee (co-chair with Lynne Talley); Ocean Carbon and Climate Change Steering Group Member; U.S. SOLAS Implementation Group member; IMBER-SOLAS Carbon Coordination Team; CLIVAR Pacific Basin Group; Partner in the European Union Carbo-Ocean Project (U.S. Coordinator); member of PICES Working Group 17: Biogeochemical Data Integration and Synthesis; member of PICES section on Carbon and Climate; Member of International Ocean Carbon Coordination Project; Member of International Pacific CLIVAR Panel, Member of Carbon Cycle Science Program Science Steering Group, Team Member of the European CARBOOCEANS; Member of U.S. SOLAS Advisory Committee.

Paul Freitag (NOAA/PMEL)
Represents the TAO Project Office on the DBCP; reported on TAO activities at the annual DBCP workshop held in Chennai, India (October 2004); represented the TAO project office at the NOAA Climate Observation Workshop (April 2005, Washington, DC); member of the OceanSITES data team charged with ensuring efficient and cost-effective OceanSITES data archiving and dissemination.

Silvia Garzoli (NOAA/AOML)
Member of the Science Advisory Council (SAC) of the Inter American Institute for Global Change research; Member of the OAR Climate Board; Member of the OAR Global Climate Coordination Team; NOAA Experts Team to provide input to the interagency process developing a U.S. Plan of Earth Observations.

Gustavo Goni (NOAA/AOML)
NASA Ocean Surface Topography; Member of Science Team.

Ed Harrison (NOAA/PMEL)
WCRP/GOOS/GCOS Ocean Observations Panel for Climate, Chair; OAR Climate Observing System Council, Chair; US GODAE Steering Team, Co-Chair; US GOOS SC; WCRP/GCOS Atmospheric Observation Panel for Climate; WCRP Working Group on Observations and Analysis; CLIVAR Global Synthesis and Observations Project; JCOMM Management Committee; WCRP Joint Scientific Committee; JISAO Senior Fellow; JIMAR Senior Fellow.

Gregory Johnson (NOAA/PMEL)
Member of U.S. CLIVAR/CO_2 Repeat Hydrography Oversight Committee, Member of U.S. CLIVAR Salinity Working Group, Associate Editor for Journal of Physical Oceanography.

Alex Kozyr (CDIAC)
Science Steering Committee of the European CarboOcean Project.; WG-17 and new Carbon & Climate Working Group of the North Pacific marine Science Organization (PICES); SOLAS implementation group IMP 3: Air-Sea Flux of CO_2 and Other Long-Lived Radiatively-Active Gases and Data Management Group.

Chris Langdon (RSMAS/MBF)
Co-organizer of workshop titled "Impacts of Increasing Atmospheric CO_2 on Coral Reefs and Other Marine Calcifiers" held 18-20 April 2005 in St. Petersburg, FL. Jointly funded by NSF, NOAA and USGS. "CO_2 chemistry effects on benthic calcifying communities and their roles in the global carbon cycle." Speaker at Ocean Carbon and Climate Change (OCCC)

Workshop held 1-4 August 2005 at WHOI - "Effect of elevated CO_2 on the cycling of organic and inorganic carbon on coral reefs."

Sydney Levitus (NOAA/NODC)
Science Panels - 1992-present Member of the NOAA Climate Change Data and Detection Panel; (formerly known as Climate and Global Change, Data and Information Management Review Panel); 1993-present Project leader for IODE/IOC "Global Oceanographic Data Archaeology and Rescue" Project; 1995-present Associate Editor for the Journal of Climate; 1995-2002 Advisor to European Community MEDAR/MEDATLAS project; 2000-present U.S. Argo Science and Implementation Panel; 2003-present Intergovernmental Panel on Climate Change, Scientific Assessment: Lead Author; 2005-present Advisor to SEADATA-NET (an Integrated Research Infrastructure Initiative (I3) including Networking, Transnational Access and Joint Research activities (dedicated to the system improvement).

Rick Lumpkin (NOAA/AOML)
PIRATA Science Steering Committee; Climate Observation Program Ocean Analysis Team.

Michael McPhaden (NOAA/PMEL)
Named a Fellow of The Oceanography Society in 2005; published several papers using TAO and related data sets, two papers as cover stories in their respective journal; serves on the International CLIVAR Pacific Panel and Global Synthesis and Observations (GSOP) Panel and the International CLIVAR/GOOS Indian Ocean Panel (IOP); member of the PIRATA SSG; member of the JCOMM Observations Coordination Group; chair of the Tropical Moored Buoy Implementation Panel (TIP); member of the OOPC/CLIVAR OceanSITES Working Group; serves as immediate past president of the Ocean Sciences Section of the American Geophysical Union; member of the Bulletin of the American Meteorological Society editorial board; serves on the organizing committee for the Tropical Atlantic Climate Variability Workshop to be held in Venice, Italy during 17-19 October 2005.

Mark Merrifield (UHSLC)
UHSLC director serves as the GLOSS Group of Experts chair, and center personnel also serve on the GLOSS Technical Steering Committee; UHSLC personnel continued to serve on the National Oceanographic Partnership Program Oceans.US Applications and Products Expert Team.

Frank Millero (RSMAS/MAC)
present, Editor-in-Chief, *Marine Chemistry;* 1995 – present, Associate Editor, *Aquatic Geochemistry;* 2004-2007, Editorial Board, *Indian Journal of Marine Sciences;* Oversight Committee for the Repeat Hydrography Program (CLIVAR, CO_2/SCC) 2002-2004; Clair C. Patterson Award Committee, 2004; ACS Geochemistry Division Medal Committee, 2004; Sigma Xi, President-Elect, 2004-2006; AMLC Executive Board, 2004.

Mark Morrissey (University of Oklahoma)
Served as PI-GCOS Coordinator in Apia, Samoa from January 2004 through May 2005. Accomplishments include: Formed PI-GCOS Steering Group from original PIRGIT group; Organized the 10th Regional Meteorological Service Director's meeting, April, 2005, Niue; Organized PI-GCOS Steering group meeting, April, 2005 Niue; Prepared PI-GCOS side event at the 10th UNFCCC meeting in Buenos Aires, Argentina, December 2004.

Mayra Pazos (NOAA/AOML)
WMO/IOC Data Buoy Cooperation Panel.

Dean Roemmich (SIO)
Active in design, coordination, and implementation of global ocean observations; serves as co-chairman of international CLIVAR's Global Synthesis and Observations Panel, as co-chairman of the Argo Science/Steering Team, and through this year as a member of US CLIVAR's Science Steering Committee; Member of the Steering Team for the SEREAD education initiative, which develops teaching units and educational materials relevant to climate and ocean observations for primary and secondary curricula in South Pacific island nations.

Christopher Sabine (NOAA/PMEL)
Member of IGBP Integrated Global Carbon Observing (IGCO) theme team; member of International CLIVAR/CLIC Southern Ocean panel; member of PICES Working Group 17: Biogeochemical Data Integration and Synthesis; mem-

ber of PICES section on Carbon and Climate; lead author for IPCC Special Report on carbon dioxide capture and storage; contributing author to IPCC Fourth Assessment Report; chair of IOC/SCOR International Ocean Carbon Coordination Project (IOCCP); scientific steering committee (SSC) member for IGBP/IHDP/ WCRP Global Carbon Project (GCP), U.S. North American Carbon Project (NACP), and U.S. Ocean Carbon and Climate Change (OCCC) Project.

Claudia Schmid (NOAA/AOML)
Argo Data Management Team, Executive Committee.

Shawn Smith (FSU)
Ocean.US IOOS Expert Team on Data Archival and Access; WCRP Working Group on Surface Fluxes.

Taro Takahashi (LDEO)
Community Service: Member of the State Of the Carbon Cycle Report (SOCCR) writing team, chapter lead; Member of the Ocean Sciences sub-committee, the AGU Fellows Committee, American Geophysical Union.

Chung-Chu Teng (NOAA/NDBC)
Co-organizer and co-technical lead for the QARTOD II Workshop (March 2005, Norfolk, VA), focusing on real-time QA/QC of ocean temperature, salinity, current, and waves data.

Rik Wanninkhof (NOAA/AOML)
SOLAS implementation group 2 member; SOLAS implementation team 2, data liaison; SOLAS summer school organizing committee; Liege Colloquium Series on fluid dynamic: air-sea gas transfer- Scientific steering committee; Guest editor, special section Journal of Marine systems air-sea gas transfer (Liege Colloquium Series); Thesis committee- William Hiscock, RSMAS; Hector Bustos, RSMAS; Qan Li, RSMAS; chair, PhD thesis committee Rob Masserini USF; examiner Habilitation J. Boutin, Paris; Reviewer of NOAA cooperative institute at Scripps (JIMO) Participant Cooperative Sensor Development Laboratory for Oceans of the University of South Florida; Meeting of CO_2 data reduction; Partner in the European Union Carbo-Ocean Project.

Robert Weller (WHOI)
Chair of the VOCALS Science Working Group for one year and continues on that group, working with Mechoso and Bretherton to coordinate activities with Chilean colleagues; Serves on the following: AGU, OS Section Executive Committee, Chair OS Section Awards Committee, International CLIVAR SSG, CLIVAR VAMOS EPIC Science Team, CLIVAR VOCALS (VAMOS Ocean Cloud Atmosphere Land Study) Science Team, Co-chair, U.S. CLIVAR Science Steering Committee., UNESCO/IOC Ocean Observations Panel for Climate (OOPC), NRC Committee on Strategic Guidance to NSF Atmospheric Sciences Division, ORION (Ocean Research Interactive Observatories Network) Executive Steering Committee, Co-chair, International Time Series Science Team; Reviewer: Journal of Physical Oceanography, Journal of Geophysical Research, Deep-Sea Research, Journal of Marine Research, Limnology and Oceanography, Geophysical Research Letters, Reviews of Geophysics, Journal of Atmospheric and Oceanic Technology, IEEE, Journal of Oceanic Engineering, Nature; Office of Climate Observations: Presentations at Annual System reviews, 2003–2005; Atlantic Oceanographic and Meteorological Laboratory: Discussions with Dr. M. Baringer, Physical Oceanography Research Division, regarding Atlantic VOS/ XBT lines; Environmental Technology Laboratory: Cooperation with Dr. C. Fairall, Clouds, Radiation, and Surface Processes Division, on field intercomparisons of meteorological data and determination of sensor accuracy; National Data Buoy Center: Cooperation with Dr. D. Conlee on deployment of radiation sensors on NDBC buoys; ongoing discussions about passing Atlantic ORS data to NHC/TPC; National Hurricane Center – Tropical Prediction Center: Discussions with Eric Blake, Tropical Analysis and Forecast Branch, about making Atlantic ORS data available; Surface Ocean Lower Atmosphere Study Solas: Member of Implementation Group 2. WHOTS surface meteorological data are freely shared with the HOTS PI community.

Lisan Yu (WHOI)
Science and implementation panels: International CLIVAR Indian Ocean Implementation Panel; National Oceanographic Part-

nership Program (NOPP) review panel; NOAA Ocean Observing System Team of Experts; NASA Ocean Vector Wind Science Team.

2. List of conferences/workshops presented at/attended

Frank Bahr (WHOI)
Climate Observation Program Workshop in Silver Spring, MD, April 2005.

Molly Baringer (NOAA/AOML)
Spring AGU meeting, May 2005; Tropical Atlantic Climate Experiment (TACE) meeting; Miami, February 3, 2005; Office of Climate Observation Review Workshop, DC, April 2005; PPBES Ship time utilization Training, Miami, FL; AGU Fall planning meeting, September 2005, Washington, D.C.

Nicholas Bates (BBSR)
SOLAS-IMBER Carbon Implementation planning meeting (Miami, December 2005); Ocean Carbon Cycle and Climate (OCCC) meeting (WHOI, August 2005); North American Coastal Carbon meeting (Boulder, Co; Sep 2005); International Carbon Dioxide Conference (Boulder, Co; September 2005).

Mark Bourassa (FSU)
Ocean Surface Topography Science Team Meeting; The Global Ocean Data Assimilation Experiment Second Symposium; FSU's Geophysical Fluid Dynamics Institute Seminar Series; NOAA Climate Observation Program 3rd Annual System Review; Ocean Vector Wind Science Team Meeting.

John Bullister (NOAA/PMEL)
Presented "Decadal Changes in Dissolved CFCs in the Eastern Basin of the North Atlantic", American Geophysical Union Meeting.

Jonathan Callahan (NOAA/PMEL)
7th International Carbon Dioxide Conference, Boulder CO – presented data management plans and solicited feedback from the CO_2 Science Team and other ocean carbon scientists (September 2005).

Francisco Chavez (MBARI)
Invited lecture at the Bevan Series on Sustainable Fisheries entitled "Ocean Variability, Climate Change, and Sustainable Marine Resources" at the University of Washington, January 27, 2005; Invited speaker at Sardine Workshop entitled "From anchovies to sardines and back: Multidecadal changes in the Pacific Ocean, Oregon State Seafood Laboratory, Astoria, Oregon, May 4, 2005; Keynote speaker at the Alexander von Humboldt international conference on El Niño entitled "Biological consequences of El Niño in the eastern Pacific", Guayaquil, Ecuador, May 17, 2005; Contributed talk entitled "Decadal coastal ocean observations of environmental variability" at the Oceanography Society meeting in Paris, France on June 7, 2005; Invited talk entitled "Biological consequences of inter-annual to multi-decadal variability" at the IRD/IFREMER laboratory in Sete, France on June 14, 2005; Invited talk entitled "Biological and chemical consequences of El Niño" at the LEGOS laboratory in Toulouse, France on June 15, 2005; Invited talk entitled "Una nueva mandala para describir la ecologia del fitoplancton marino" at the Universidad de Barcelona on June 17, 2005; Invited talk entitled "Climate and ocean variability in relation to living resources" at workshop in Corvallis, Oregon on August 11, 2005 to help NOAA define what is needed for Ocean Color Climate Data Records; Invited talk entitled "Climate and ocean variability in relation to fish (and other large marine organisms) abundance" at workshop on Pacific-Atlantic Sea Turtle Assessment, 22-23 August, 2005 in La Jolla; Invited talk entitled "U.S. West Coast Carbon Cycling" at The North American Continental Margins (Coastal CO2) Workshop, 21-23 September, 2005 in Boulder, CO; Invited talk entitled "Climate variability, ecological processes and biogeochemical cycling in the California Current" at a Joint ECO-UP–EUR-OCEANS workshop on Upwelling Systems impacted by global change, 26-30 September, 2005 in Casablanca, Morocco.

Steven Cook (NOAA/AOML)
20th meeting of the Data Buoy Cooperation Panel (DBCP); OCO Annual System Review, April 2005; JCOMM – SOT-3 meeting, Brest, France.

Meghan Cronin (NOAA/PMEL)
"KESS Workshop", University of Rhode Island, Sep 29-30, 2005; U.S. CLIVAR Summit, Process Studies and Model Improvement Panel, Aug 15-18, 2005; "KESS and Beyond" science meeting at JAMSTEC, Yokohama, Japan, 15 June 2005; "Workshop on the Application of EPIC2001 Data for Testing and Improving Coupled Atmosphere-Ocean Models" at UW/APL in May 2005; NOAA Climate and Global Change Postdoctoral Program Symposium, April 2005.

Craig Engler (NOAA/AOML)
20th meeting of the Data Buoy Cooperation Panel (DBCP).

Chris Fairall (NOAA/ETL)
25th Session of the Joint Scientific Committee for the WCP, World Climate Research Program, Moscow, Russia, 1-6 March 2004. Presentation: The WCRP Working Group on Surface Fluxes; *Seventh Annual Meeting of the WCRP/CLIVAR VAMOS Panel*, NOAA-OGP, Guyaquil, Ecuador, 22-25 March 2004; Presented poster at *Office of Climate Observation Annual System Review*, NOAA, Silver Spring MD, 13-15 April 2004/2005; *Second Workshop on High-Resolution Marine Meteorology*, NOAA, Silver Spring, MD, 15-16 April, 2004; Presented paper at *Focus 2 Working Group for the International SOLAS Implementation Plan*, Surface Ocean-Lower Atmosphere Study, IGBP, Montreal, Canada, 17-19 May 2004; *First International CLIVAR Scientific Conference*, WCRP, 21-25 June 2004; Posters given: 1) Cloud forcing of the surface energy budget of the ITCZ/Cold Tongue complex in the tropical Eastern Pacific, 2) Investigation of air-sea interaction and cloud processes in the EPIC stratocumulus region; *Annual Meeting of the WCRP/CLIVAR VAMOS Panel*, NOAA-OGP, Mexico City, Mexico, 9-11 March 2005; MD, 25-27 April 2005.

Richard Feely (NOAA/PMEL)
Fall meeting AGU, San Francisco – chaired special session on Repeat Hydrography (December 2004); Co-chaired Calcification workshop St Petersburg FL (April 2005); Presentation at NOAA COSP Annual Meeting (May 2005); Presentation at Princeton cooperative institute carbon meeting, Princeton NJ (June 2005); Presentation at the OCCC Summer Workshop, Woods Hole MA (August 2005); Coastal carbon meeting. Boulder CO – Presentation on OCCC Program (September 2005); 7th International Carbon Dioxide Conference, Boulder CO – Program Committee and poster presentation on the Repeat Hydrography Program and panelist on air-sea fluxes of CO_2 (September 2005); Testimony on impacts of Anthropogenic CO_2 in the Oceans before the Senate Commerce Committee, September 21, 2004.

Silvia Garzoli (NOAA/AOML)
CLIVAR Atlantic Meeting; January 31 – February 2, 2005, Miami; Tropical Atlantic Climate Experiment (TACE) meeting; Miami, February 3, 2005; Office of Climate Observation Annual System Review Workshop, DC, April 2005; South Atlantic Argo Regional Data Center, Cape Town, South Africa, May 2005.

Gustavo Goni (NOAA/AOML)
Office of Climate Observation Review Workshop, DC, April 2005; Ocean Surface Topography Science Working Team Meeting, Tampa, November 2004.

Ed Harrison (NOAA/PMEL)
October 12 CDEP review OGP, 2004; Nov 1-3, 2nd GODAE Symposium (St. Petersburg, FL); November 3-5 US GOOS SC Dallas; November 8-12 CLIVAR GSOP, Boulder; November 22-23, COSC DC; November 30-December 3 POGO, Brest/IOC, Paris. 2005: December 6-9 Carbon Coordination, IOC/Paris; December Ocean 500 at University of Washington, OSB 410; February 9-12 MAN4, Paris; Feb 21-23 GOOS SC8…Melbourne AU; March 7-9 SOT Brest France; March 14-18 JSC26 Guyaquil, EC; April 11-15 AOPC-11 Geneva; Apr 25-28 COSC Annual Meeting; May 9-12 OOPC-10 Geneva; May 19-22 SBSTA Bonn; Jun 1-3 WGOA, GISS; August 16-18 GCOS Chairs, WMO; September 17-21, JCOMM-II, Halifax.

Dave Hosom (WHOI)
Climate Observation Program Workshop in Silver Spring, MD, April 2005.

Gregory Johnson (NOAA/PMEL)
American Geophysical Union Fall meeting in San Francisco, 13-17 December 2004; First Argo DMQC Workshop in La Jolla, 11-13 April

2005; Climate Observations Program 3rd Annual System Review in Silver Spring, 25-27 April 2005; Argo APEX Users' Group Workshop in Seattle, 19-21 September 2005.

Robert Key (Princeton University)
Presented Tracing the World Oceans with D14C, invited presentation, Wiener Physikalisches Kolloquium, Vienna, Austria, December 13, 2004; Tracing the world oceans with D14C, invited presentation, Notre Dame Physics Colloquium, October 5, 2005.

Alex Kozyr (CDIAC)
CarboOcean meeting, January 2005; WG-17 meeting during the PICES XIII Annual Meeting, September 2005; Synthesis Project Science Team meeting at Princeton, June 2005.

Sydney Levitus (NOAA/NODC)
JCOMM Science Meeting, Climate Change and Variability in the Global Ocean (INVITED), September 2005; U. Delaware Warming of the World Ocean, 1955-2003 and Earth's Heat Balance (INVITED), September 2005; NCEP Seminar Warming of the World Ocean, 1955-2003, June 2005; International Marine Data and Information Systems (IMDIS) Brest, France "World Ocean Database 2001": An Ocean Profile-Plankton Database for Ocean and Climate-System Research, June 2005; U. Maryland Warming of the World Ocean, 1955-2003, May 2005; IFREMER Brest, France Warming of the World Ocean, 1955-2003, May 2005; IOC/IODE XVIII (Paris) Results of GODAR Project, April 2005; NASA Sea Level Panel Meeting Ocean Thermosteric Sea Level, 1955-2003, April 2005; NOAA/OGP/C2D2 Panel meeting Ocean Data Archaeology and Rescue & Ocean Analysis, March 2005; University of Bergen Salinity Variability, 1955-1998 (INVITED), March 2005; University of Bergen Building Ocean Profile-Plankton Databases for Climate System Research (INVITED), March 2005; University of Bergen Warming of the World Ocean and Earth's Heat Balance, 1955-2003 (INVITED), March 2005; American Meteorological Society Annual Meeting-Suki Manabe Symposium Variability of Heat Content and Salinity for the World Ocean, 1955-2003 (INVITED PAPER), January 2005, American Geophysical Union Annual Meeting Variability of Ocean Heat Content, Freshwater Content, and Steric Sea Level for the World Ocean, 1955-2002, December 2004, GODAR WESTPAC Meeting (JODC, Tokyo, Japan), November 2004; Status of the IOC Global Oceanographic data Archaeology and Rescue Project (INVITED).

Rick Lumpkin (NOAA/AOML)
OCO Annual System Review, April 2005; CLIVAR Atlantic meeting, Tropical Atlantic Climate Experiment (TACE) Workshop; CBLAST meeting; EMC Workshop on Air-Sea fluxes; 10th PIRATA meeting; 20th meeting of the Data Buoy Cooperation Panel (DBCP).

J. M. Lyman (NOAA/PMEL)
Attendance at the EPIC Workshop in Seattle, WA, May 11-13.

Christopher Meinen (NOAA/AOML)
CLIVAR Atlantic meeting, Jan.-Feb. 2005, Miami, FL.; Office of Climate Observation Review Workshop, April 2005; PPBES Ship time utilization Training, Miami, FL.

Mark Merrifield (UHSLC)
January 2005, presented "GLOSS - Multipurpose Global Sea Level Observing System," World Conference on Disaster Reduction in Kobe Japan; Participated in workshop sponsored by the Japan Meteorological Agency in Tokyo, Japan on sea level variability, presented papers on the GLOSS network in the Pacific and GPS@TG issues; March 2005, participated in the International Coordination Meeting for the Development of a Tsunami Warning and Mitigation System for the Indian Ocean, Paris France, presented "GLOSS Core Network as Part of the Indian Ocean Tsunami Warning System"; April 2005, presented "GLOSS - Review and Status Report for the IOTW," Second International Coordination Meeting for the Development of a Tsunami Warning and Mitigation System for the Indian Ocean in Grand Baie, Mauritius, presented "GLOSS: Global Sea Level Observing System" at The 2nd Experts Consultation Meeting for the Establishment of a Regional End-to-end Multi-hazard Early Warning System in Southeast Asia in Bangkok Thailand; an update on multiple-use tide gauge stations was presented at the JCOMM/OPA meeting in Silver Spring, MD; June 2005, presented "Sustainable sea level stations: an example of a multiple hazard, multiple function observation and communication system" at the Asia Pacific

All Hazards Workshop in Honolulu Hawaii; June 2005, presented “GLOSS and The Southeast Asia Tsunami Warning System” at the High-level Expert Meeting on Technical Options for Disaster Management Systems: Tsunamis and Others in Bangkok Thailand; July 2005, presented “Coastal Sea Level Networks - IOC GLOSS network” at the IOC and ISDR Study Tour on National Tsunami Warning System Implementation in Hawaii for High Level Administrators in the Indian Ocean Responsible for Tsunami Warning Activities in Honolulu Hawaii; August 2005, presented “GLOSS - Global Sea Level Observing System: IOTWS Standards and Sites” at the First Session of the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS-I) in Perth Australia; September 2005, attended the International Workshop Large Recent Tsunamis in the Indian Ocean and Other Regions held in Santiago, Chile, presented two papers, one on the use of multipurpose sea level stations for tsunami warning and the second on the GCS/GLOSS network of sea level monitoring stations.

Frank Millero (RSMAS/MAC)
F.J. Millero, J.W. Morse, H. Bustos-Serrano, The formation of whitings on the Little Bahama Bank, ASLO Summer Meeting, June 19-24, 2005, Santiago de Compostela, Spain; J. M. Santana-Casiano, M. González-Dávila and F. J. Millero, Oxidation of Fe(II) in seawater, ASLO Summer Meeting, June 19-24, 2005, Santiago de Compostela, Spain; Invited lecturer, “The Carbon Dioxide System in the Oceans,” Florida State University, Tallahassee, FL, April, 2005.; Invited lecturer, Chemical Oceanography Course, Universidad Politecnica de Catalunya, Barcelona, Spain, June 25 to July 1, 2005; Invited lecturer, F.J. Millero, Chemical Oceanography, Universidad de Las Palmas, Las Palmas de Gran Canaria, Spain, July 2 to 12, 2005; Invited Lecturer, F.J. Millero, “Carbonate Parameters (pH Alkalinity, Total CO_2, Conductivity), Advanced Training Workshop on Southeast Asia Regional Carbon and Water Issues at the National Central University, Chung-Li and San Yat-Sen University, Kaohsiung, Taiwan, November 15-28, 2005.

Robert Molinari (NOAA/AOML)
OCO Annual System Review, April 2005.

Mark Morrissey (University of Oklahoma)
Klatt, M.D. and M. Morrissey: PACRAIN, presented at the AMS meeting San Diego, CA, 2005; 2003, RANET possibilities in the Pacific, RANET Steering Group meeting presented in Honolulu, HI; PI-GCOS progress and plans, presented at the WMO RAV Data Management Workshop, Melbourne, Australia, November/ December 2004; PI-GCOS progress and plans, presented at the 10^{th} UNFCCC meeting, Buenos Aires, Argentina, Dec. 2004; PI-GCOS activities, presented at the CAPABLE workshop held in Apia, Samoa, May 2005.

Peter Niiler (SIO)
DBCP, October 16-19, Chennai, India: “Hurricane Drifter Deployment Results” – 2004, (Bill Scuba, Jan Mozel and Peter Niiler). Bill Scuba is the co-organizer of the DBCP Technical Session in 2004 and 2005; JIMO/NORI International Workshop on the Western Pacific Circulation, November 19, 2004, La Jolla, CA: “Western Pacific Circulation from Drifters and Altimeters”; GODAE International Workshop, November 2, 2004, St. Petersburg, FL: “The dynamics of ocean surface circulation studied using altimeter, Lagrangian drifter and wind data” (Nikolai Maximenko of University of Hawaii for Peter Niiler); Invited lecture, Office of Climate Observation Annual System Review, April 27, 2005, Silver Spring, MD: “Ocean Circulation Observations for Climate”; Invited Lecture, May 3, 2005, The Jet Propulsion Laboratory, Pasadena, CA: “The importance of observing surface circulation of the oceans.”

Mayra Pazos (NOAA/AOML)
Argos Users Regional Conference; 20th meeting of the Data Buoy Cooperation Panel (DBCP).

Tsung-Hung Peng (NOAA/AOML)
AGU 2004 Fall Meeting, 8-12 December 2004, San Francisco, CA, December 2004; CMC CO2 meeting at Princeton University, Princeton, N.J., June 1-3, 2005; ASLO summer meeting 2005, Santiago de Compostela, Spain, June 19-24, 2005.

Susan Postawko (University of Oklahoma)
Improving communications and observations across the Pacific: The Pacific RANET Project, presented at the WMO RAV Data Management Workshop, Melbourne, Australia, November/

December 2004; Postawko, S., Ah Poe, A., Morrissey, M., The Pacific RANET Project, presented at the annual meeting of the American Geophysical Union, San Francisco, Dec. 2004; Postawko, S. and M. Morrissey: Improving Hydro-Meteorological Monitoring in Sparsely Observed Regions on Pacific Islands, presented at the Annual AMS meeting, San Diego, CA, 2005; An update on the SPaRCE program, presented at the 10th Regional Meteorological Service Directors meeting, Niue, April 2005; Community involvement and understanding of climate observations: The Schools of the Pacific Rainfall Climate Experiment, presented at the CAPABLE workshop held in Apia, Samoa, May 2005.

Richard Reynolds (NCDC)
Blended SST Analysis Changes and Implications for the Buoy Network. Presented at the Climate Observation Annual System Review, Silver Spring, MD, April 23-27, 2005; GCOS SST/Sea-Ice Working Group Progress. Presented at the Tenth Ocean Observations Panel for Climate Meeting, Geneva Switzerland, May 9-12, 2005; Plans to Develop a High Resolution SST Analysis at NCDC. Presented at the Sixth GODAE High Resolution SST Pilot Project Meeting, Exeter, UK, May 16-20, 2005; A Daily Blended Analysis for Sea Surface Temperature. Presented at the ORA/NCDC Scientific Presentations of Climate-Related Activities Workshop, Asheville, NC, September 14, 2005; Smith, T.M., and R.W. Reynolds, Prospects for Improving SST Analyses. Presented at Development of Improved Observations Workshop, NASA, Greenbelt, MD, September 28-30, 2005; Zhang, H.-M., R.W. Reynolds, and T.M. Smith, Adequacy of In Situ Observing System in the Satellite Era for Climate SST. Presented at the AMS 2005 Annual Meeting, San Diego, CA, January 9-13, 2005; Visit during July 2005 to work with Professor Dudley Chelton at the College of Oceanic and Atmospheric Sciences, Oregon State University, in Corvallis, OR to develop and test the daily OI analysis. A trip report summarizing the progress was circulated to his SST colleagues for comments. A great deal of progress was made during this visit due to frequent consultations with Chelton and due to the excellent working conditions at Oregon State.

Ignatius Rigor (UW)
Invited speaker, co-presented at MARCDAT-II Meeting, Exeter, UK, October, 2005; co-presented at JCOMM-II Scientific Conference, Halifax, Canada, September 2005; co-authored talk at JCOMM-II Scientific Conference, Halifax, Canada, September 2005; INVITED talk at Polar Bear Specialists Group Meeting, June 2005; INVITED talk at Ice University Workshop, Canadian Ice Service, Ottawa, Canada, May 2005; Attended NOAA Arctic Ocean Observing System: Ice Thickness Component, NOAA Ocean Climate Observing System Review, Silver Spring, MD, Apr. 2005; co-authored Forecasting the Condition of Sea Ice on Weekly to Seasonal Time Scales, *NOAA Ocean Climate Observing System Review*, Silver Spring, MD, Apr. 2005; co-presented on Arctic and Global Climate Change, *NOAA Ocean Climate Observing System Review*, Silver Spring, MD, Apr. 2005; INVITED speaker on Sea Ice, *Pacific Arctic Group Symposium on Circulation and Ecology of the Pacific Arctic Shelves and Connection to Deep Basins*, Arctic Science Summit Week, Kunming, China, Apr. 2005; INVITED Keynote Speaker at *Gordon Research Conference on Polar Marine Science*, Ventura, CA, Mar. 2005; INVITED speaker at *Arctic Climate Science Priorities Workshop, NOAA Climate Program Office*, Silver Spring, MD, Feb. 2005; INVITED at *Eos Trans. AGU*, Fall Meet. Suppl., Dec. 2004; co-authored an article in the *E*os Trans. *AGU*, Fall Meet. Suppl., Dec. 2004; co-authored National Oceanic and Atmospheric Administration (NOAA) Arctic Climate Change Studies: A Contribution to IPY, *Eos Trans. AGU*, Fall Meet. Suppl., Dec. 2004; co-authored a paper in *Eos Trans. AGU*, Fall Meet. Suppl., Dec. 2004; Co-authored presentation in *Eos Trans. AGU*, Fall Meet. Suppl., Dec. 2004; Observed Changes at the Surface of the Arctic Ocean, *Eos Trans. AGU*, Fall Meet. Suppl., Dec. 2004; Made contributions to Proc. Arctic Climate Impacts Assessment (ACIA) International Symposium on Climate Change in the Arctic, Reykjavik, Nov. 2004; participated in the International Symposium on Climate Change in the Arctic, Reykjavik, Nov. 2004; NOAA Arctic Climate Change Studies: A U.S. Contribution to Arctic Council Responses to the ACIA, Proc. Arctic Climate Impacts Assessment (ACIA) International Symposium on Climate Change in the Arctic, Reykjavik, Nov. 2004.

Christopher Sabine (NOAA/PMEL)
CO_2 Science Team/VOS pCO_2 meeting, Miami, FL (October 2004); PMEL Seminar Series, Seattle, WA; (title: What hydrographic sections can tell us about the global carbon cycle) (October 2004); PICES XIII meeting, Honolulu, HI; (chair session S8 on North Pacific Carbon Cycle Changes, lead author on poster, coauthor on 3 talks) (October 2004); CLIVAR Reanalysis Workshop, Boulder, CO (November 2004); Scripps Seminar, San Diego, CA; (title: The Oceanic Sink for Anthropogenic CO_2, Past, Present and Future) (November 2004); International Ocean Carbon Stakeholders Meeting, Paris; (co-organizer and chair of meeting) (December 2004); World Universities Network Video Seminar, Seattle, WA; (title: Ocean uptake of CO_2 resulting from human activity over the last 200 years) (April 2005); NOAA/PMEL Program overview, Seattle, WA; (talk: PMEL carbon program) (May 2005); CICS carbon workshop, Princeton, NJ; (talk: Decadal Changes in Ocean Carbon Uptake: Some intriguing findings from the first 3 years of the CLIVAR/CO_2 Repeat Section Program) (June 2005); Global Carbon Project SSG meeting and mini conference on vulnerabilities in carbon-climate-human system, Paris France; (talk: Vulnerabilities of the calcium-carbonate cycle: positive and negative feedbacks) (June 2005); JISAO retreat, Seattle, WA; (talk: Decadal Changes in Ocean Carbon Uptake: Some intriguing findings from the first 3 years of the CLIVAR/CO_2 Repeat Section Program) (June 2005); OCCC Meeting, Woods Hole, MA; (invited talk: The Oceanic Sink for Anthropogenic CO_2: Past, Present and Future) (August 2005); PMEL presentation to Congressional Aids; (talk: PMEL carbon program) (August 2005); US CLIVAR Panel Workshop, Keystone, CO; (invited talk: The US Ocean Carbon and Climate Change Program and opportunities for Carbon-CLIVAR connections) (August 2005); OCCC/NACP Coastal CO_2 Workshop NACM, Boulder, CO; (invited talk: OCCC/NACP Joint Coastal Carbon Studies) (September 2005); 7th International CO_2 Meeting, Broomsfield, CO; (Invited talk: Decadal changes in ocean carbon uptake) (September 2005); Ocean Carbon open house, Broomsfield, CO; (organizer and host) (September 2005).

Claudia Schmid (NOAA/AOML)
10th PIRATA Meeting, Fortaleza, Brazil, December 13-15, 2004; Office of Climate Observation Review Workshop, DC, April 2005.

Shawn Smith (FSU)
85th AMS Annual Meeting; Office of Climate Observation Annual System Review; UNOLS RVTEC Annual Meeting; 1st CLIVAR GSOP Panel Meeting; CLIVAR Workshop on Ocean Reanalysis; 1st WCRP Working Group on Surface Fluxes Meeting; The Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) Initiative. Presentations at the *2004 UNOLS Research Vessel Technical Enhancement Committee Meeting*, St. Petersburg, FL, 2004.

Derrick Snowden (NOAA/AOML)
JCOMM – SOT-3 meeting, Brest, France.

Taro Takahashi (LDEO)
Keynote address, Global and regional distribution of surface water pCO2 over the oceans. International Conference on the Ocean CO2, Tsukuba, JAPAN, Jan., 2004; Invited presentation, Decadal Time Scale Change of the Surface Water pCO_2 over the North Pacific. The North Pacific Carbon Chemistry Workshop, Seattle, WA, June 2004; Olafsson, J., Takahashi, T., Olafsdottier, S. R. and Danielsen, M., Carbon dioxide and nutrients in Atlantic, Arctic and Polar waters of the N-Atlantic. Challenger Conference on Marine Sciences, Liverpool, UK, Sept. 15, 2004; Matter, J., Goldberg, D. and Takahashi, T., In-situ testing of geological carbon dioxide sequestration in basalt aquifers: Results from a pilot study in the Palisade diabase (New York). Chapman Conference, San Diego, CA, Jan., 2005; Fladeland, M. M., Dobosy, R. Takahashi, T. and Sullivan, D. Eddy flux measurements in the Southern Ocean marine boundary layer using long-duration, low-altitude robotic aircraft. NASA Suborbital Flight Program meeting, Washington, D. C. January 31, 2005; Takahashi, T., Feely, R.A., Wanninkhof, R. and Sutherland, S. C. Decadal change of the surface water pCO_2 in the North Pacific: A synthesis of 35 years of observations. European Geophysical Union meeting, Vienna, Austria, May 2005; Matter, J. M. Goldberg, D. S. and Takahashi, T. Tests of In-Situ CO_2-Water-Rock Reactions During Carbon Dioxide Injections in Basaltic Rocks: Toward permanent sequestration of CO_2. Annual Meeting, DoE Carbon dioxide Sequestration conference, Washington, D. C., 2005;

Feely, R. A., Takahashi, T. and Wanninkhof, R. Sources and Sinks of Carbon Dioxide in the Surface Oceans (2005). Goldschmidt Conference, Moscow, ID, August 2005; Gruber, N., Mikaloff-Fletcher, S. E., Jacobson, A. R., Gloor, M., Sarmiento, J. L. and Takahashi, T. Oceanic sources and sinks for atmospheric CO_2. 7th International Carbon Dioxide Conference, Boulder, CO, September 2005; Corbière, A, Metzl, N. Reverdin, G., Brunet, C., Ramonet, M. and Takahashi, T. (2005). Interannual variability of the carbon dioxide system and air-sea CO2 fluxes in the high latitude of the North Atlantic Ocean: 1993-2004 (SURATLANT Program). 7th International Carbon Dioxide Conference, Boulder, CO, September 2005.

Rik Wanninkhof (NOAA/AOML)
First International SOLAS science meeting, Halifax, Canada (September 2004); International air-sea interaction conference Kyoto, Japan - invited speaker (October 2004); Fall meeting AGU, San Francisco – presentation (December 2004); Calcification workshop St Petersburg FL (April 2005); Liege Colloquium Series on fluid dynamic: air-sea gas transfer-presentation (May 2005); Princeton cooperative institute carbon meeting, Princeton NJ (June 2005); SOLAS summer school. Cargèse, Corsica, France – lecturer (September 2005); Coastal carbon meeting. Boulder CO - invited participants and breakout session chair (September 2005); International carbon dioxide conference, Boulder CO - poster presentation (September 2005).

Robert Weller (WHOI)
Participated in workshop on the Application of EPIC2001 Data for Improving and Testing Coupled Atmosphere-Ocean Models, Seattle, May 2005; the VOCALS Science and Implementation Workshop, Corvallis, November, 2004; the VAMOS Panel in Mexico City, Climate Observation Program Workshop in Silver Spring, MD; Plueddemann, A.J. and R.A. Weller, 2005. Meteorology and air-sea fluxes from ocean reference stations, *NOAA Office of Climate Observation Workshop*, 25-27 April 2005, Silver Spring, MD.

Josh Willis (JPL, Pasadena, CA)
Presentations at the Ocean Surface Topography Science Team Meeting in St. Petersburg, FL, Nov. 4-6, 2004, the 2004 AGU fall meeting in San Francisco, 13-17 December 2004, the NASA Sea Level Workshop in Landover, MD, April 11-12, 2005, and the 2005 Meeting of the International Association of Meteorology and Atmospheric Sciences (IAMAS) in Beijing, China, August 2-11, 2005.

Lisan Yu (WHOI)
November 2004: CLIVAR Ocean Reanalyses Workshop. Boulder, Colorado, Invited participation; December 2004: The AGU Fall meeting. San Francisco, CA., Invited presentation; January 2005: US CLIVAR Atlantic workshop. Miami, Florida; February 2005: NOAA/NASA workshop on Satellite Measurements of Ocean Vector Winds: Present Capabilities and Future Trends. Miami, Florida, Invited presentation; March 2005: NASA Ocean Vector Wind Science Team annual meeting. Seattle, WA., Invited participation; March 2005: The Indian Ocean Climate Symposium sponsored by the World Climate Research Program's CLIVAR project and the Intergovernmental Oceanographic Commission's Global Ocean Observing System. Hobart, Australia, Invited presentation; April 2005: NOAA's Office of Climate Observation 3rd Annual System Review workshop. Silver spring, Maryland May 2005: The AGU Spring meeting. New Orleans, Louisiana; August 2005: The NOAA/WHOI CICOR and OCCI seminar series on "The Role of Indian Ocean on Climate", Woods Hole, invited presentation.

Jia-Zhong Zhang (NOAA/AOML)
Thirteenth International Conference on Flow Injection Analysis (ICFIA 2005), Las Vegas, Nevada, USA, April 2005.

3. Outreach (e.g., education initiatives, press/media interviews, public lectures)

Molly Baringer (NOAA/AOML)
Interviewed Philadelphia Inquirer reporter Tony Wood; Interviewed book author Dallas Murphy who volunteered for the September 2005 Western Boundary Current Time Series cruise on the R/V RONALD H. BROWN.

Nicholas Bates (BBSR)
SOLAS summer school lecture on time-series

and sustained observations (Cargese, Corsica, September 2005); BBSR Board of Trustees presentation on time-series and sustained observations (May 2005); Invited talk at Princeton University (October 2005).

Gustavo Goni (NOAA/AOML)
Oceanography lecture and deployment of floats and drifters from the Semester At Sea M/V Explorer, April 2005.

Rick Lumpkin (NOAA/AOML)
Oceanography lecture and deployment of floats and drifters from the Semester At Sea M/V Explorer, Brazil to South Africa, September 2005; Supervised the deployment of an "Adopt A Drifter" buoy that has been co-adopted by Congressional School (Virginia, USA) and Elsies River High School (South Africa). Archbishop and Nobel Laureate Desmond Tutu and Captain Jeremy Kingston of the MV *Explorer* launched the drifter on 25 September 2005.

Archbishop Desmond Tutu (left) and Captain Jeremy Kingston (right) deploy a drifter from the MV Explorer's fantail.

Sydney Levitus (NOAA/NODC)
Consulted by major media including NY Times, ABC news.

Christopher Meinen (NOAA/AOML)
Interview book author Dallas Murphy; Data have been used for educational purposes at the University of Miami and at public schools across the nation.

Frank J. Millero (RSMAS/MAC)
Sloan Conference Mentor, 2004.

Derrick Snowden (NOAA/AOML)
Sea Keepers Society Workshop, Ft. Lauderdale, FL.

Robert Weller (WHOI)
The December 2004 stratus cruise also hosted a teacher from NOAA's Teacher at Sea Program (Mary Cook), as well as NOAA program managers and educational staff. During the cruise, the teacher assisted with science operations including mooring deployments and recoveries. She also hosted broadcasts, wrote daily logs, took photos, and interviewed science members and crew. This information was used to communicate with her classroom, as well as those of other land-based teachers. All of the video, pictures, and logs are available at http://www.ogp.noaa.gov/stratus/. The cruise also served as the germination point for the first NOAA Teacher at Sea book, describing Mary Cook's experiences on the cruise (http://www.noaanews.noaa.gov/stories2005/s2417.htm). Additionally, the ship played host to visiting delegations of local officials and school children during its port calls.

Guest lecturer on Air-Sea Fluxes in "Introduction to Physical Oceanography" class, 2002-2004; Co-Advisor (with W. Jenkins), Postdoc Burkard Baschek 2003-2005; Member, NE-COSEE Science Advisory Group 2004 – present; Participant, Ocean Literacy Online Workshop 2004–2005; Participant, Roundtable Discussion on Ocean Exploration, U-Mass Dartmouth, January 2004; Participant, NE-COSEE Telling Your Story Workshop, January 2004; Presenter, U.S. ambassador to Barbados visit to NOAA ship RONALD H. BROWN; (resulting article in Barbados Advocate newspaper, March 2005).

APPENDIX C

The Ten Climate Monitoring Principles

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems is required.

3. The details and history of local conditions, instruments, operating procedures, data processing algorithms, and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.

4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.

5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional, and global observing priorities.

6. Operation of historically uninterrupted stations and observing systems should be maintained.

7. High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.

8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation.

9. The conversion of research observing systems to long-term operations in a carefully planned manner should be promoted.

10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.

APPENDIX D

Acronyms

AAAS	American Association for the Advancement of Science
ABL	Atmospheric Boundary Layer
ADCP	Acoustic Doppler Current Profiler
ADP	Adopt a Drifter Program
AGU	American Geophysical Union
AMMA	African Monsoon Multidisciplinary Analyses
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSU-B	Advanced Microwave Sounding Unit – Channel B
AMVER	Automated Mutual assistance Vessel Rescue system
AOML	Atlantic Oceanographic and Meteorological Laboratory
APDRC	Asia-Pacific Data Research Center
APL	Applied Physics Laboratory
ARCs	Applied Research Centers
ArcIMS	Arc Internet Map Server
ARPEGE-CLIMAT	Climate Research Project on Small and Large Scales (France)
ASIMET	Air-Sea Interaction Meteorology system
BAKOSURTANAL	National Coordinating Agency for Surveys and Mapping, Indonesia
BATHY	Bathythermograph format for data exchange
BMRC	Bureau of Meteorology Research Centre (Australia)
BoM	Bureau of Meteorology (Australia)
BPR	Bottom Pressure Recorder
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency) (Germany)
CARINA	CARbon dioxide IN the Atlantic
C&GC	Climate and Global Change
CCHCO	CLIVAR and Carbon Hydrographic Data Office
CCRI	Climate Change Research Initiative
CCSP	Climate Change Science Program
CDC	Climate Diagnostics Center
CDIAC	Carbon Dioxide Information Analysis Center
CDP	Climate Data Portal
CEOF	Complex Empirical Orthogonal Function
CFD	Computer Flow Dynamics
CGPS	Continuously Operated GPS
CICOR	Cooperative Institute for Climate and Ocean Research
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIPS	Climate Information and Prediction Services Project
CLIVAR	CLImate VARiability and Predictability
C-MAN	Coastal-Marine Automated Network
CMAP	CPC Merged Analysis of Precipitation
CMORPH	CPC MORPHing Technique
COLA	Center for Ocean, Land, and Atmosphere Studies
COAPS	Center for Ocean-Atmospheric Prediction Studies
COOP	Coastal Ocean Observations Panel (GOOS)
COP	Climate Observation Program

CORC	Consortium on the Ocean's Role in Climate
COSC	Climate Observing System Council
COSP	Climate Observations and Services
CLIVAR	Climate Variability and Predictability Program
CPC	Climate Prediction Center
CPO	Climate Program Office
CPPA	Climate Prediction Program for the Americas
CPRDB	Comprehensive Pacific Raining Database
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTD	Conductivity, Temperature, Depth
DAC	Data Assembly Center
DART	Deep Ocean Assessment and Reporting of Tsunamis (Buoy)
DBCP	Data Buoy Cooperation Panel
DCP	Data Collection Platform
DCS	Data Collection System
DMC	Drought Monitoring Center
DODS	Distributed Ocean Data System
DOE	Department of Energy
DSL	Digital Subscriber Line
DWBC	Deep Western Boundary Current
ECCO	Estimating the Circulation and Climate of the Ocean
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EOF	Empirical Orthogonal Function
EPIC	Eastern Pacific Investigation of Climate
ERA40	ECMWF ReAnalysis-40
ERS	Earth Remote-sensing Satellite
ESDIM	Environmental Services Data and Information Management (NOAA)
ESRI	Environmental Systems Research Institute
ETL	Environmental Technology Laboratory
EVAC	Environmental Verification and Analysis Center
FAO	Food and Agriculture Organization (UN)
FGDC	Federal Geographic Data Committee
FLOAT	Argo subsurface profiling floats
FRX	Frequently Repeated XBT
FS	Frequently Sampled Line
FSU-COAPS	Florida State University Center for Ocean-Atmosphere Prediction Studies
FTE	Full Time Equivalent
FY	Fiscal Year
GAINS	GLOSS Development in the Atlantic and Indian Oceans
GAPP	GEWEX Americas Prediction Project
GCC	Global Carbon Cycle
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GCTE	Global Change and Terrestrial Ecology Program
GCRMN	Global Coral Reef Monitoring Network
GDC	Global Drifter Center
GDP	Global Drifter Program
GEOSAT	Geodesy Satellite
GEWEX	Global Energy and Water-cycle Experiment
GIS	Geographic Information System
GLOSS	Global Sea Level Observing System
GODAE	Global Ocean Data Assimilation Experiment
GODAR	Global Oceanographic Data Archaeology and Rescue Project

GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
GOSUD	Global Ocean Surface Underway Data project
GPCP	Global Precipitation Climatology Project
GPS	Global Positioning System
GPS@TG	Co-located GPS systems at tide gauge stations
GSOP	Global Synthesis and Observations Panel of CLIVAR
GTS	Global Telecommunications System
GTSPP	Global Temperature-Salinity Profile Program
HD	High Density Line
HRX	High Resolution XBT
HURDAT	Atlantic Basin Hurricane Database
IAI	Inter-American Institute for Global Change Research
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IDOE	International Decade of Ocean Exploration
IES	Inverted Echo Sounder
IFREMER	Institut français de recherche pour l'exploitation de la mer (French Research Institute for Exploitation of the Sea) (France)
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrated Global Carbon Observing team
IHO	International Hydrographic Organization
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IMET	Improved METeorological instrument
IMMA	International Maritime Meteorological Archive format
IOC	Intergovernmental Oceanographic Commission
IOCCP	International Ocean Carbon Coordination Project
IODE	International Oceanographic Data and information Exchange
IOOS	Integrated Ocean Observing System
IOOS-DMAC	Integrated Ocean Observing System – Data Management and Communication
IOTWS	Indian Ocean Tsunami Warning System
IPRC	International Pacific Research Center
IPY	International Polar Year
IR	Infrared
IRD-Brest	L'Institut de recherché pour le developpement – Brest (France)
IRI	International Research Institute for Climate Prediction
ISCCP	International Satellite Cloud Climatology Project
ITCZ	Inter-Tropical Convergence Zone
IUGG	International Union of Geodesy and Geophysics
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JASL	Joint Archive for Sea Level
JASON	Not an acronym but the name of a join French/US altimeter mission
JCOMM	Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology
JCOMMOPS	Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology Observing Platform Support
JGOFS	Joint Global Ocean Flux Survey
JIMAR	Joint Institute for Marine and Atmospheric Research, University of Hawaii
JIMO	Joint Institute for Marine Observations
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JMA	Japan Meteorological Agency
J-OFURO	Japanese Ocean Flux data sets with Use of Remote sensing Observations
JPL	Jet Propulsion Laboratory
JTA	Joint Tariff Agreement
KE	Kuroshio Extension

KEO	Kuroshio Extension Observatory
KESS	Kuroshio Extension System Study
LAS	Live Access Server
LD, LDX	Low Density Sampling Line
LLNL	Lawrence Livermore National Laboratory
MAN	Management Committee (JCOMM)
MAO	Marine and Aviation Operations (NOAA)
MBT	Mechanical Bathythermograph
MEDS	Marine Environmental Data Services
MICOM	Miami Isopycnic Coordinate Ocean Model
MJO	Madden-Julian Oscillation
MOC	Meridional Overturning Circulation
MOCHA	Meridional Overturning, Circulation and Heat Transport Array
MOU	Memorandum of Understanding
MS	Microsoft
NACP	North American Carbon Program
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
ncBrowse	Graphical netCDF File Browser
NDBC	National Data Buoy Center
NCDC	National Climatic Data Center
NCDDC	National Coastal Data Development Center
NCEP	National Centers for Environmental Prediction
NEAR-GOOS	North-East Asian Regional GOOS
NERC	National Environmental Research Council
NESDIS	National Environmental Satellite, Data, & Information Service
netCDF	network Common Data Form
NGDC	National Geophysical Data Center
NGO	Non-Governmental Organization
NIC	National Ice Center
NIH	National Institutes of Health
NIWA	National Institute of Water and Atmospheric Research (New Zealand)
NMFS	National Marine Fisheries Service
NMHS	National Meteorological and Hydrological Services
NMRI	Naval Medical Research Institute
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOPP	National Ocean Partnership Program
NORPAX	North Pacific Experiment
NOS	NOAA Ocean Service
NOSA	NOAA Observing System Architecture
NRC	National Research Council
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NTC	National Tidal Centre, Australia
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWS-PR	National Weather Service Pacific Region
NVODS	National Virtual Ocean Data System
MON	NWS Marine Observation Network
OAFlux	Objectively Analyzed air-sea heat Fluxes
OAR	Office of Oceanic and Atmospheric Research
OCCC	Ocean Carbon and Climate Change Program

OCCI	Ocean Climate Change Institute
OceanSITES	Ocean Sustained Interdisciplinary Time series Environmental Observatory
OCO	Office of Climate Observation
ODINAFRICA	Ocean Data and Information Network for Africa
OGP	Office of Global Programs
OMAO	Office of Marine and Aviation Operations
OOPC	Ocean Observations Panel for Climate
OpeNDAP	Open Source Project for Network Data Access Protocol
OSMC	Observing System Monitoring Center
PacificGOOS	Pacific Global Ocean Observing System
PACIS	Pan-American Climate Information System
PACS	Pan American Climate Studies
PCES	North Pacific Marine Science Organization
PDO	Pacific Decadal Oscillation
PEAC	Pacific ENSO Applications Center
PHOD	Physical Oceanography Division
PIES	Pressure Gauge Equipped Inverted Echo Sounder
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
PMEL	Pacific Marine Environmental Laboratory
PMO	Port Meteorological Officer
PNA	Pacific North America
PNNL	Pacific Northwest National Laboratory
POGO	Partnership for the Observation of the Global Oceans
PP&I	Program, Planning & Integration
QA	Quality Assurance
QSCAT	Seawinds on QuikScat
RRP	ENSO Rapid Response Project
RSMAS	Rosenstiel School of Marine and Atmospheric Science
R/V	Research Vessel
RVIB	Research Vessel / Ice Breaker
RVSMDC	Research Vessel Surface Meteorology Data Center
SABOM	South African Bureau of Meteorology
SAC	Special Analysis Center
SAF	Subantarctic Front
SAMOS	Shipboard Automated Meteorological and Oceanographic System
SAR	Synthetic Aperture Radar
SAZ	Subantarctic Zone
SCPP	Seasonal-to-Interannual Climate Prediction Program
SCMI	Southern California Marine Institute
SCOR	Scientific Committee for Ocean Research
SDE	Spatial Database Engine
SEACOOS	Southeast Atlantic Coastal Ocean Observing System
SEAFLUX	Ocean Surface Turbulent Flux Project
SEARCH	Study of Environmental Arctic Change
SEAS	Shipboard Environmental data Acquisition System
SEAS	Windows version of the SEAS shipboard software
SEC	South Equatorial Current
SEREAD	Scientific Educational Resources and Experience Associated with the Deployment of Argo profiling floats in the South Pacific Ocean
SI	Seasonal-to-Interannual
SIO	Scripps Institution of Oceanography
SIO-ECPC	Scripps Institution of Oceanography-Experimental Climate Prediction Center
SLP	Sea Level Pressure
SLP-PAC	Sea Level Program in the Pacific

SOC	Southampton Oceanography Centre
SOI	Survey of India
SOLAS	Surface Ocean-Lower Atmosphere Study
SOOP	Ship-of-Opportunity Program
SOOPIP	Ship-of-Opportunity Implementation Panel
SOI	Southern Oscillation Index
SOT	Ship Observations Team
SPARCE	South Pacific Rainfall Climate Experiment
SPCZ	South Pacific Convergence Zone
SRDC	Surface Reference Data Center
SSG	Scientific Steering Group
SSM/I	Special Sensor Microwave Imager
SSP	Sea Surface Pressure
SST	Sea Surface Temperature
START	Global Change System for Analysis, Research, and Training
STD-C	Standard C
STF	Subtropical Front
SURFRAD	Surface Radiation Budget Network
TAO	Tropical Atmosphere Ocean Array
TAV	Tropical Atlantic Variability
TESAC	Temperature, Salinity, Currents (format for data exchange)
TMI	TRMM Microwave Imager
TOGA	Tropical Ocean Global Atmosphere Program
TOGA/COARE	Tropical Ocean Global Atmosphere / Coupled Ocean-Atmosphere Response Experiment
TOPEX	Ocean TOPography Experiment
TRACKOB	Track observation
TRITON	Triangle Trans-Ocean Buoy Network
TRMM	Tropical Rainfall Measurement Mission
TSG	Thermosalinograph
UHSLC	University of Hawaii Sea Level Center
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
UNOLS	University – National Oceanographic Laboratory System
UOT	Upper Ocean Thermal
UOTC	Upper Ocean Thermal Center
UPS	Uninterruptible Power Supply
URI	University of Rhode Island
USB	Universal Serial Bus
USCG	United States Coast Guard
USIABP	U.S. Interagency Arctic Buoy Program
USGCRP	U.S. Global Change Research Program
UW	University of Washington
VOS	Volunteer Observing Ship
VOSClim	WMO Volunteer Observing Ship Climate project
WCRP	World Climate Research Program
WDC-A	World Data Center-A for Oceanography
WFS	Web Feature Service
WGASF	Working Group on Air-Sea Fluxes
WHO	World Health Organization
WHOI	Wood’s Hole Oceanographic Institution
WMO	World Meteorological Organization
WMS	Web Map Service
WOCE	World Ocean Circulation Experiment

WWE	Westerly Wind Event
WWW	The World Weather Watch of WMO
XBT	Expendable Bathythermograph
XCTD	Expendable Conductivity Temperature Depth