The *in situ* Global Ocean Observing System - Progress since OceanObs1999

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Abstract

An *in situ* global ocean observing system for the physical climate system was conceived largely at the Ocean Observations conference in St. Raphael in September 1999. It was recognized that society did not have adequate information about the state of the world ocean or its regional variations to address a range of important societal needs, and the subsequent work by the marine carbon community and others in the ocean science and operational communities led to an agreed international plan that was described in the GCOS Implementation Plan (GCOS-92, 2004). We here describe the efforts that have been made to reach these goals. Thanks to these efforts, most of the ice free ocean above 2000m is now being observed systematically for the first time, and a global repeat hydrographic survey and selected transport measurements supplement these networks.

The system is both integrated and composite. It depends upon satellite and *in situ* networks with observations of the same variable from different sensors. In this way optimum use is made of all available platforms and sensors to maximize coverage and attain maximum accuracy. Wherever feasible observations are transmitted in real time or near-real time because of the desirability to use every observation for as many purposes as possible, from short term ocean forecasting to estimation of century-long trends. Because our historical knowledge of oceanic variability is limited, we are learning about the sampling requirements and needed accuracies as the system is implemented and exploited, and the system will evolve as technology and knowledge improve.

Key *in situ* networks are world-ocean coverage with surface drifting buoy and profiling float (Argo) arrays; basin-spanning repeat lines of XBTs and hydrographic/carbon/tracer observations; a handful of fully time-resolving moored reference sites, a global tropical mooring array; coastal tide gauges that are geo-centric referenced; selected transport observations at key locations; and the highest quality observations of surface and near-surface variables from commercial and research ships. The progress in implementation of these arrays is described and the role of the WMO-IOC Joint Commission on Oceanography and Marine Meteorology (JCOMM) in these networks is described.

Key words: Global Ocean Observing System (GOOS), GCOS, JCOMM, drifting buoys and data buoys and global tropical moored buoys (DBCP, TAO, PIRATA, RAMA), OceanSITES, sea level (GLOSS), hydrographic surveys (IOCCP), Argo, Volunteer Observing Ships (VOS), Ships of Opportunity (SOOP).

1. Introduction

The delivery of ocean services to society depends upon an observing system design based upon the historical ocean data record and special-purpose model studies; operation of an observing system adequate to support the services desired; analysis systems to integrate all available observations and permit the extraction of ocean information; and appropriate assimilation/forecast systems to deliver forecasts of the desired extent into the future. During the GODAE period effort has been invested in each of the above categories and significant progress has been made in each. Here we shall review briefly the efforts that have been made to agree and implement a sustained *in situ* global ocean observing system that will support GODAE's objectives.

An effective observing system depends upon many data system elements. In particular measurements must be made from sensors whose characteristics are understood and acceptable; the observations from the senor (including appropriate metadata) must be transported to a facility where they can be made use of immediately (or assembled together) and given preliminary quality control; provision for access for the wide range of potential users must be made; integration with other observations must also occur in order that delayed-mode quality control can be done for more exacting application. These issues will be addressed in another paper in this session. Here we shall focus only on the coordination of the collection of *in situ* observations

Successful operation of a global observing system requires that there be coordination of activities on a number of levels. Sensors and best practices need to be agreed. Deployment opportunities need to be identified and instruments delivered to take advantage of them; where no opportunistic deployment is feasible, timely provision of special deployment efforts needs to be made. The data coverage of the system needs to be monitored along with sensor lifetimes and provision made to anticipate where gaps will appear so that deployment can be arranged. Given that a number of nations participate in each of the observing networks and both 'operational' and 'research' programs are involved, this monitoring/system management function is non-trivial and critical. We shall classify the range of needed activities "Observing Program Support". We shall discuss briefly some of the issues that fall into this category.

The Global Climate Observing System (GCOS) Implementation Plan (GCOS-92, 2004) called for phased implementation of an integrated and composite satellite and *in situ* observing system, with related data management and analysis activities. The ten-year implementation ramps are shown in Figure 1, which also shows the year-by-year progress in reaching the ten-year goals and the status to date.

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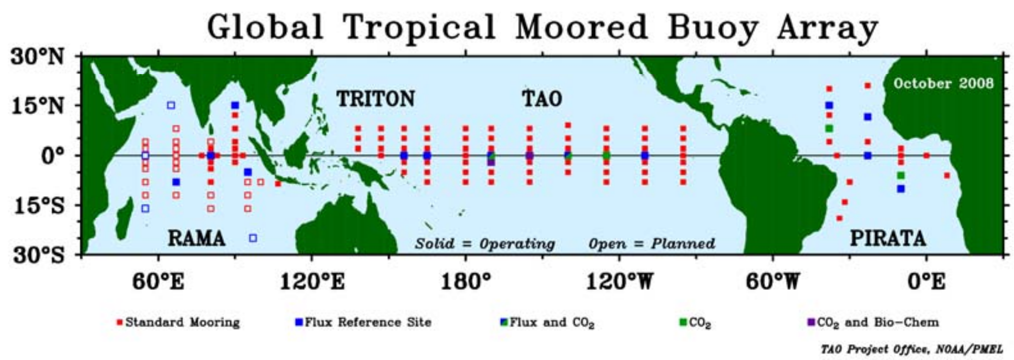
Figure 1: Status of the in situ Global Ocean Observing System against targets defined in the GCOS Implementation Plan and accepted by JCOMM

There are two different classes of observing activities underway *in situ* – those from fixed points and those whose location varies with time. Fixed point observations are made either from moorings or from repeated occupation of stations. Observations whose location vary with time are made from platforms that move as a result of the motion of the ocean or of a moving vessel. Some moving platforms are thought to follow the motion of water parcels fairly well ("Lagrangian").

2. Fixed Point Observing Networks

The networks of this type are the Global Tropical Moored Array, the OceanSITES program, the Global Sea Level Observing System (GLOSS), and some station-keeping repeat hydrographic surveys.

Global Tropical Moored Array (http://www.pmel.noaa.gov/tao/*).* The near-equatorial upper ocean with its strong and quite variable currents poses many observational challenges and arrays on fixed mooring are the fundamental observing system building block in each of the oceans. In the tropical Pacific the TAO/TRITON array was fully deployed by 1999, while in the Atlantic the PIRATA (Prediction and Research Moored Array in the Atlantic) array has expanded to nearly double in size from 10 moorings in 1999 to the current 20). The Indian Ocean RAMA array (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) was begun during the GODAE period and is about 50% complete.



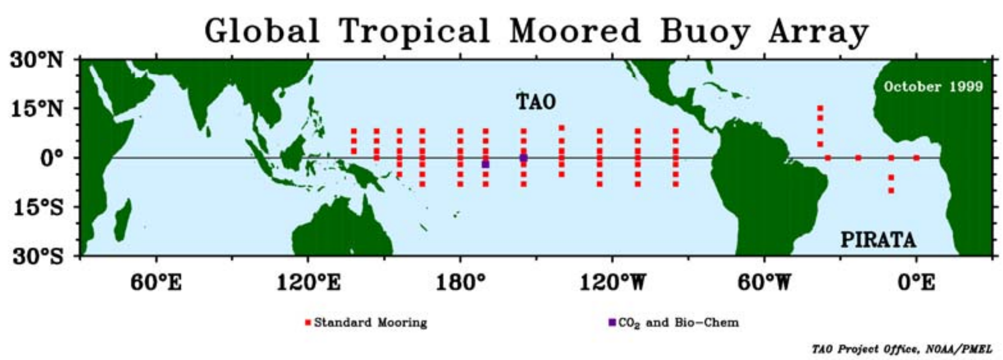


Figure 2 shows how the Global Tropical Moored Buoy Array has evolved since October 1999 (top) to present (October 2008, bottom)

OceanSITES (http://www.oceansites.org/*).* OceanSITES has plans to deploy and maintain 89 ocean reference stations (including transport, flex and multi-sensor platforms) that will sample as comprehensively as is feasible. There are currently 43 references stations.

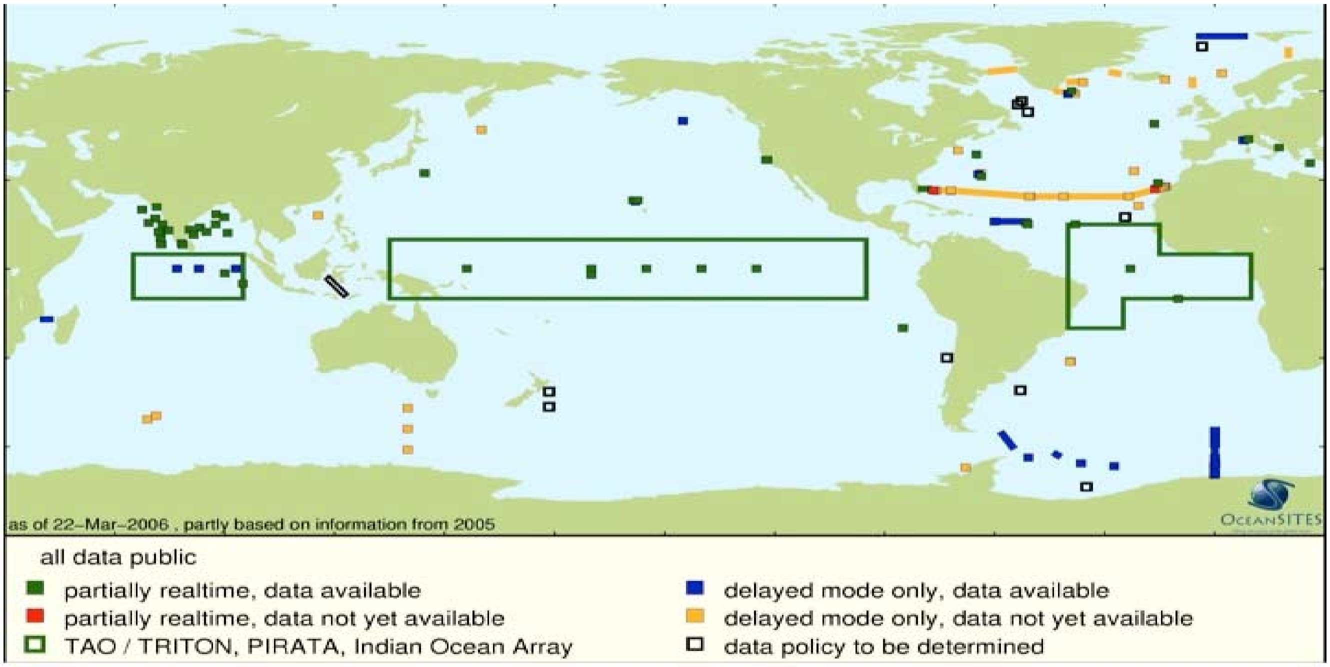


Figure 3: There are plans to deploy and maintain 89 Ocean Reference Stations (43 are now in service)

GLOSS (http://www.gloss-sealevel.org/). This is one of the oldest network of the global ocean observing system, with some tide gauges having been maintained since the 19th century. Important improvements in the number of gauges reporting high frequency data and in real time have taken place since 1999 (figure 4). In support of GODAE, Fast Delivery mode (□available within 1 month of collection) and real time (available 15 minutes to 3 hours) GLOSS data are assembled and provided by the University Hawaii Sea Level Center (UHSLC). Final Delayed mode data are provided by the British Oceanographic Data Centre (BODC). The status of real time reporting stations and recently collected time series are available at the Sea Level Station Monitoring Facility, maintained by the Flanders Marine Institute (VLIZ, http://www.vliz.be/gauges/).

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Figure 4: Important improvements in the number of gauges reporting high frequency data and in real time have taken place during the GODAE period.

Repeat Hydrographic Surveys (http://www.ioccp.org/). The global repeat hydrographic survey is an essential observing system element for understanding the controls and distribution of natural and anthropogenic carbon, circulation tracers, and a large suite of biogeochemically and ecologically important chemicals in the ocean interior, including nutrients and oxygen. The surveys (figure 5) also remain critical for understanding ocean changes below 2 km (52% of global ocean volume), and their contributions to global freshwater, heat and sea-level budgets.

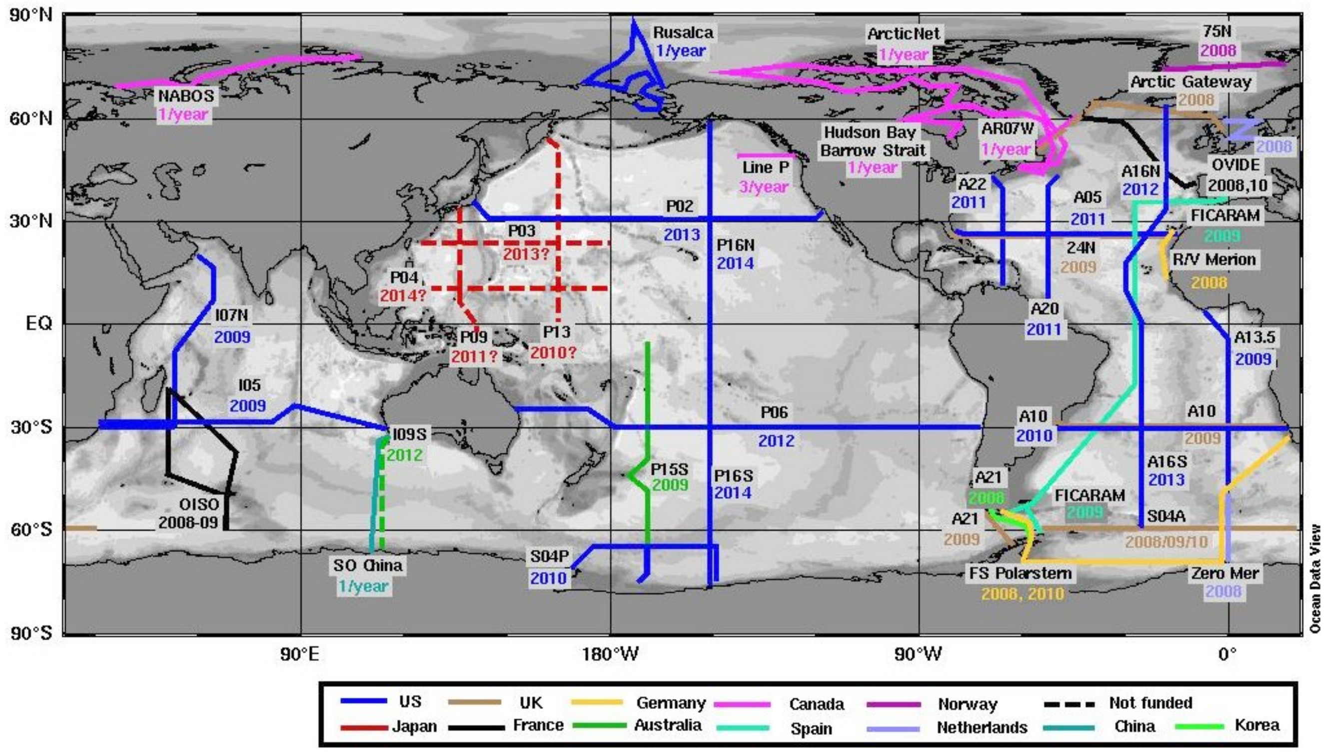

Figure 5: Current and planned carbon hydrography sections. These sections are carried out as part of the CLIVAR/CO_2 global repeat survey of WOCE hydrographic sections, scheduled to be completed in 2012. The field program is approximately 75% completed.

3. Moving Observation Networks

The networks of this type are the Argo profiling float program, the surface drifting buoy network, the Arctic and Antarctic buoy programs, the XBT network and the Volunteer Observing Ship (VOS) scheme.

*Surface Drifting Buoy Program (*http://www.jcommops.org/dbcp/ , http://www.aoml.noaa.gov/phod/dac/gdp.html *).* Planning for this array was begun in 1967 as part of the First GARP (Global Atmospheric Research Programme) Experiment, designed to provide ocean surface information from regions not sampled by the volunteer observing ships. It plays a fundamental role in providing accurate 'bulk' SST observations and surface pressure observations to the integrated observing system. The network reached its initial number goal of 1250 drifters in 2005, but has not yet achieved the desired geographical coverage of a drifter per 5x5 degree area of the ice-free ocean.

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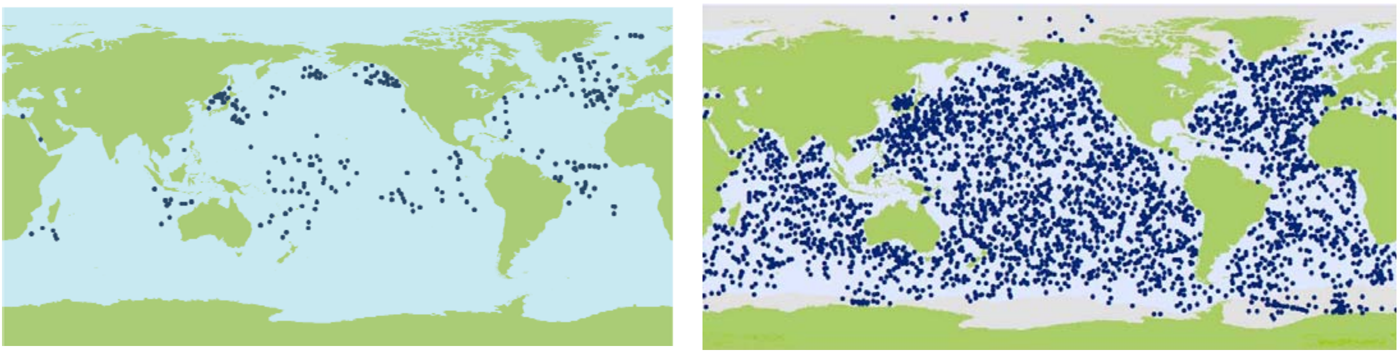
Figure 6: The surface drifting buoy network reached its initial implementation goal of 1250 in 2005.

Argo Profiling Float Program (http://www.argo.ucsd.edu/). This array was developed as a GODAE observing system initiative and has grown from an idea to reaching its initial implementation goal of 3000 operating floats, distributed relatively homogeneously throughout the world's ocean basins between 60^o N and 60^o S, in November 2007 (figure 7). Although is has not yet reached its desired geographical coverage of a float per 3^o x 3^o region, the Argo array is providing a nearly global picture of the world's oceans every ten days, and the development of instruments capable of operating in ice-covered regions is extending this into higher latitudes in both hemispheres.



(a) (b)

Figure 7: Global distribution of Argo profiling floats (a) 30 November 2001, (b) 30 November 2008. The array has grown to its initial implementation goal of 3000 floats during GODAE

International Arctic Buoy Program. This network of buoys is used to monitor synoptic-scale fields of sea level pressure, surface air temperature, and ice motion throughout the Arctic Ocean (figure 8).

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Figure 8: The Arctic ocean observing buoys have more than doubled during GODAE (24 in 1999 and 54 in 2008), and graphically illustrate the decrease in sea ice during that time.

*Voluntary Observing Ship scheme (*http://www.bom.gov.au/jcomm/vos/*).* In this effort, research, private and commercial crews report a variety of air-sea variables, either from automated sensors or by direct measurement. This is perhaps the oldest of the global marine observing system and has its roots in the observations recorded routinely in ship logs. It uniquely is capable of providing information about marine surface atmospheric pressure, air temperature and humidity and clouds.

*Ship of Opportunity Programme (SOOP) (*http://www.jcommops.org/soopip/*).* XBTs, TSGs, pCO2. In this program ships either deploy sensors (XBTs or XCTDs) or pump water to laboratory sensors. Most of the historical upper ocean data set was developed in this way. Over the past decade there has been an effort to focus on repeat sections in order to explore systematically space- and time-scales of oceanic variability (figure 9).

4. Observing System Support

Sustaining the required coverage in space and time of observations requires substantial coordination and at many different levels. The JCOMM Observations Program Group (OCG) aspires to provide coordination of the sustained observing activities, but there is also need for coordination with research ocean observing programs.

One fundamental challenge is to provide the needed sensors to platforms that can deliver them to the needed locations in the needed time frame. This requires anticipating where sensors are likely to fail, having replacement sensors available, knowing about deployment opportunities and being able to ship the needed sensors in order to take advantage of the opportunities.

This is accomplished largely through informal networks of individuals and companies that have been developed over recent decades. With ever-changing patterns of global marine commerce and of reduced staffing ashore and onboard, the effort required is considerable. It is also qualitatively different from that required to maintain national meteorological networks. The success of the system depends upon voluntary contributions to a great extent. Society owes a great debt to the global merchant marine community that seldom is appropriately acknowledged. And of course, the global ocean research community's sea-going fleet and chief scientists also are fundamental contributors.

The advantages of a systematic framework to support these observing system status monitoring and deployment activities became clear as progress in implementation was achieved. JCOMMOPS (the JCOMM *in situ* Observing Platform Support Centre, http://www.jcommops.org) was established in 2001, and the development of observing system monitoring software continues as this is written. Successful implementation depends fundamentally upon near-real transmission of both observations and relevant metadata. Important progress has been made in both areas over the past decade, and will be addressed in this session in the data system presentation.

Making the most effective linkages with the shipping community is essential but remain a work in progress. There is an urgent need for a common website that carries maps for deployment opportunities from the research, military and commercial fleets of all nations. Efforts by the research community to provide more systematic access to information are being led the Partnership for Observations of the Global Ocean (POGO), and discussions are underway concerning the feasibility of an enhanced capability JCOMM Observing Program Support Center (OPSC).

5. Sustaining the Observing System

There are many challenges to be addressed in maintaining what has been achieved over the past decade. All programs face nontrivial increases in the cost of hardware and salaries. The VOS program is feeling the impact of cutbacks in national weather services support of the program, particularly reduction in the number of Port Meteorological Officers, and changes in the patterns and staffing and security concerns affecting the global merchant shipping fleet. The XBT program also strains to achieve its coverage because of changes in the routing of outfitted ships. The Argo and surface drifting buoy programs require special deployment assistance in areas remote from commercial shipping. The global hydrographic survey is strongly affected by increases in the availability and cost of operating blue water research ships. Sustaining moored arrays requires dedicated ships and personnel able to go where and when replenishment is needed or data return suffers, and vandalism restricts effectiveness in some regions. Data sharing of tide gauge observations is problematic in some key regions.

The ocean community has demonstrated during the GODAE period that a global ocean observing system can be implemented, and can provide critical data to support global ocean forecasting and analysis. With the observations being used ever more effectively, it is hoped that the coming decade will see not only continuity but also increased coverage including more variables. From this foundation observing system, important progress will be made in ecosystem management, sustainable fisheries, weather and climate forecasting, marine operations, and the safety of life at sea.

Acknowledgement
Acknowledgement and thanks are due to all, who through their efforts, deliver observations day after day and sustain the ocean observing system.

References

Bourles, B., R. Lumpkin, M.J. McPhaden, F. Hernandez, P. Nobre, E. Campos, L. Yu, S. Planton, A. Busalacchi, A.D. Moura, J. Servain, and J. Trotte (2008) The PIRATA Program: History, Accomplishments, and Future Directions. *Bull. Amer. Meteor. Soc*., 89, 1111-1125.

Cunningham S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. J.-M. Hirschi, L. M. Beal, C. S. Meinen, and H. L. Bryden, Science, (2007) Temporal variability of the Atlantic meridional overturning circulation at 26.5°N, *Science*, 317, 935–938.

GCOS (2004) Implementation Plan for the Global Observing System for Climate in support of the UNFCCC, GCOS 92, WMO/TD No. 1219.

Johnson, G.C., S. Mecking, B.M. Sloyan, and S.E. Wijffels (2007) Recent bottom water warming in the Pacific Ocean. *J. Climate*, 20(21), 5365–5375.

Johnson, G.C., S.G. Purkey, and J.L. Bullister (2008) Warming and freshening in the abyssal southeastern Indian Ocean. *J. Climate*, 21, doi: 10.1175/2008JCLI2384.1, 5351–5363.

Johnson, G. C., and S. C. Doney (2006) Recent western South Atlantic bottom water warming, *Geophysical Research Letters*, 33, L14614, doi:10.1029/2006GL026769.

Johnson, G.C., S.G. Purkey, and J.M. Toole (2008) Reduced Antarctic meridional overturning circulation reaches the North Atlantic Ocean. *Geophys. Res. Lett*., 35, L22601, doi: 10.1029/2008GL035619.

Johnson, G. C. and N. Gruber (2007) Decadal water mass variations along 20oW in the Northeastern Atlantic Ocean. *Progress in Oceanography*, 73, 277––295.

Lumpkin, R. and M. Pazos (2007) Measuring surface currents with SVP drifters: the instrument, its data, and some recent results. *Chapter 2 of /Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics,/ Ed. A. Griffa, A. D. Kirwan, A. J. Mariano, T. Ozgokmen and T. Rossby, Cambridge University Press.*

McPhaden, M.J., G. Meyers, K. Ando, Y. Masumoto, V.S.N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, and W. Yu (2008). RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Am. Meteorol. Soc*., in press.

McPhaden, M.J., T. Delcroix, K. Hanawa, Y. Kuroda, G. Meyers, J. Picaut, and M. Swenson (2001) The El Niño/Southern Oscillation (ENSO) Observing System. *In: Observing the Ocean in the 21st Century*. Australian Bureau of Meteorology, Melbourne, Australia, 231-246.

Sabine, C.L., R.A. Feely, F.J. Millero, A.G. Dickson, C. Langdon, S. Mecking, and D. Greeley (2008) Decadal changes in Pacific carbon. *J. Geophys. Res*., 113, C07021, doi: 10.1029/2007JC004577.

Mecking, S., C. Langdon, R.A. Feely, C.L. Sabine, C.A. Deutsch, and D.-H. Min (2008): Climate variability in the North Pacific thermocline diagnosed from oxygen measurements: An update based on the U.S. CLIVAR/CO2 Repeat Hydrography cruises. *Global Biogeochem. Cy*., 22, GB3015, doi: 10.1029/2007GB003101.

Murata, A., Y. Kumamoto, S. Watanabe, and M. Fukasawa (2007) Decadal increases of anthropogenic CO2 in the South Pacific subtropical ocean along 32°S, *J. Geophys. Res*., 112, C05033. doi:10.1029/2005JC003405.

Rintoul, S. R. (2007) Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific Oceans. *Geophysical Research Letters*, 34, L06606, doi:10.1029/2006028550.

Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz (2008) Expanding oxygen-minimum zones in the tropical oceans. *Science*, 320(5876), 655–658.

Tanhua, T., A. Kortzinger, K. Friis, D. W. Waugh, and D. W. R. Wallace (2007) An estimate of anthropogenic CO2 inventory from decadal changes in oceanic carbon content. *Proceedings of the National Academy of Sciences of The United States of America* 104(9), 3037–3042.