The Sustained Global Ocean Observing System For Climate

Climate Observation Division
NOAA Climate Program Office

- Who we are
- Why we observe the ocean
- How we observe the ocean

National Oceanic and Atmospheric Administration

Introduction

The ocean, which covers 71 percent of the Earth's surface, exerts profound influence on the Earth's climate system by moderating and modulating climate variability and altering the rate of long-term climate change. The ocean's enormous heat capacity and volume provide the potential to store 1,000 times more heat than the atmosphere. The ocean also serves as a large reservoir for carbon dioxide, currently storing 50 times more carbon than the atmosphere. Eighty-five percent of the rain and snow that water the Earth comes directly from the ocean, while prolonged drought is influenced by global patterns of ocean temperatures. Coupled ocean-atmosphere interactions such as the El Niño-Southern Oscillation (ENSO) influence weather and storm patterns around the globe. Sea level rise and coastal inundation are among the most significant impacts of climate change, and abrupt climate change may occur as a consequence of altered ocean circulation.

Observation is the foundation for all climate information. NOAA deploys a global ocean observing system to fulfill diverse functions, including both its climate and weather forecast missions[1]. Due to high thermal inertia, the "memory" of the ocean is a hundred years or more for certain weather- and climate-relevant phenomena, whereas the memory of the global atmosphere is about a week or less. Consequently, the forecast of weather conditions beyond a week or two requires ocean information, and, particularly under storm conditions, even short-term weather forecasts are improved by including ocean-atmosphere interaction. The longer the time-scale, the more important the ocean becomes. Predictions of climate conditions in the seasons and decades ahead, therefore, depend critically on ocean data.

A key feature of the ocean is its constant motion, which redistributes heat and the freshwater the ocean receives from precipitation, snow and ice-melt. The ocean and atmosphere influence global climate in different but complementary ways as they exchange heat and freshwater. For example, evaporation, which adds water vapor that is less dense than air to the atmosphere, induces upward mixing and subsequent release of energy into the upper atmosphere with widespread influence on weather and climate; conversely, precipitation, which adds freshwater to the ocean, makes its surface layer less salty and less dense, reducing downward mixing in the ocean. Cooling the lower atmosphere makes the air more stable, reducing upward mixing, whereas cooling the upper ocean makes surface water denser, increasing downward mixing. Because the relative influences of such phenomena vary regionally, it is important to observe the ocean in many locations. In the tropics, surface ocean warming associated with El Niño increases evaporation and convection, altering distant rainfall patterns; in high latitude regions, atmosphere-induced ocean cooling is a major contributor to global phenomena such as the meridional overturning circulation.

Goal

The goal of the Climate Observation Division's Ocean Climate Observation Program[2] is to build and sustain the *in situ* ocean component of a global climate observing system that will respond to the long-term observational requirements of operational forecast centers, international research programs, and major scientific assessments. The Division works toward achieving this goal by providing funding to implementing institutions across the nation, promoting cooperation with partner institutions in other countries, continuously monitoring the status and effectiveness of the observing system, and providing overall programmatic oversight for system development and sustained operations.

Importance of Ocean Observations

Ocean observations are critical to climate and weather applications of societal value, including forecasts of droughts, hurricanes and storm surges, predictions of El Niño, and projections of decadal to multi-decadal climate change, while providing information vital to management of ocean ecosystems and human adaptation activities in response to climate variability and change.

Observational Objectives

The ocean observing system for climate strives to deliver continuous instrumental records and global analyses of:

- **Sea Surface Temperature and Surface Currents,** to identify significant patterns of climate variability.
- **Ocean Heat Content and Transport,** to better understand the extent to which the ocean sequesters heat, to identify where heat enters the ocean and where it emerges to interact with the atmosphere, and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change.
- **Air-Sea Exchanges of Heat, Momentum, and Freshwater,** to identify changes in forcing functions driving ocean conditions and atmospheric conditions, and to elucidate oceanic influences on the global water cycle.
- **Sea Level,** to identify changes resulting from trends and variability in climate.
- **Ocean Carbon Uptake and Content,** to better understand the extent to which the ocean sequesters CO_2 and how cycling among ocean-land-atmosphere carbon reservoirs varies on seasonal-to-decadal time scales.
- **Sea Ice Thickness and Extent,** to elucidate climate variability and rapidly changing climate at high latitudes.

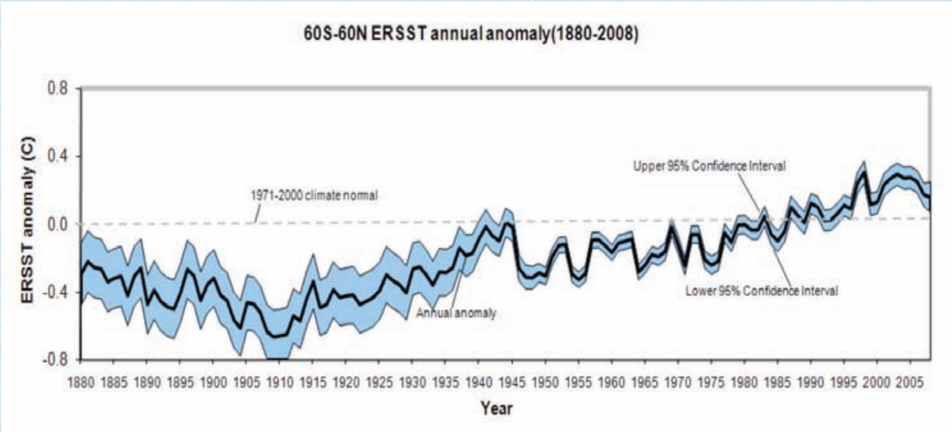
[1] Ocean observations also support coastal ocean applications, marine hazard warning systems (e.g., tsunami warnings), transportation, marine environment and ecosystem monitoring, as well as naval and other applications.

[2] The Climate Observation Division can be contacted at climate.observation@noaa.gov.

Ocean Science Drivers

Sea Surface Temperature and Surface Currents

Currents – Observed to identify significant patterns of climate variability.



Extended Reconstructed Sea Surface Temperature (ERSST) anomalies, for the period 1880 to present, from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php). ERSST is derived from ship, buoy, and other data that are assembled, quality controlled, and made available as the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). ERSST utilizes statistical methods that blend sparse historical observations with the more comprehensive data sets available today. This reconstruction shows that sea surface temperature, when averaged annually over the regions from 60° South to 60° North, while variable on timescales of decades, has increased over the past century. The lower precision of old measurements can be seen in the broader spread of temperatures encompassed by the light blue shaded bands, which provide a measure of uncertainty in the annual averages.

- The ocean communicates with the atmosphere via its surface. In this regard, sea surface temperatures (SSTs) are of particular interest because (1) the ocean covers 71 percent of the Earth's surface; therefore, SSTs constitute a large component of global average temperature, which is a fundamental measure of global climate change; (2) SSTs determine the fluxes of heat and water to/from the atmosphere, which, in turn, control sequestration of heat in the ocean, impact amounts and patterns of precipitation, and influence large-scale circulation patterns in the atmosphere; (3) SSTs are a key ocean property that controls air-sea exchange of carbon dioxide, which, in turn, influences sequestration of CO_2 in the ocean; (4) SSTs are an indicator of patterns of climate variability with known impacts on humans and ecosystems, e.g., El Niño, Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO); and (5) SSTs are known to correlate with tropical cyclone activity.

- SST at any location reflects how much heat enters or escapes the surface of the ocean (for example, as a consequence of direct solar radiation or greenhouse forcing that causes heating from above); how much heat is transported to or from other locations as a consequence of winds and ocean currents; and how much heat escapes from the bottom of the ocean mixed layer into the deeper ocean as a consequence of downwelling or vertical diffusion of heat.

- From the standpoint of numerical weather prediction, SSTs are an essential boundary condition on weather models; indeed, SST is the key ocean property that must be specified in order to model the physical behavior of the atmosphere. As a consequence, and because the ocean mixes much more slowly than the atmosphere, seasonal climate predictions may be possible because the slowly changing ocean boundary conditions retain a measure of deterministic predictability. In addition, decadal climate variability reflects ocean (SST) anomalies, which, in turn, reflect changes in ocean circulation and subsurface heat transport that occur on longer time scales.

- Thus while observed SSTs alone provide the information necessary to characterize the ocean's influence on weather, long-term observations of ocean properties and elucidation of ocean processes that underlie prediction of future SSTs are essential to making seasonal climate predictions and to characterizing decadal climate variability and change.

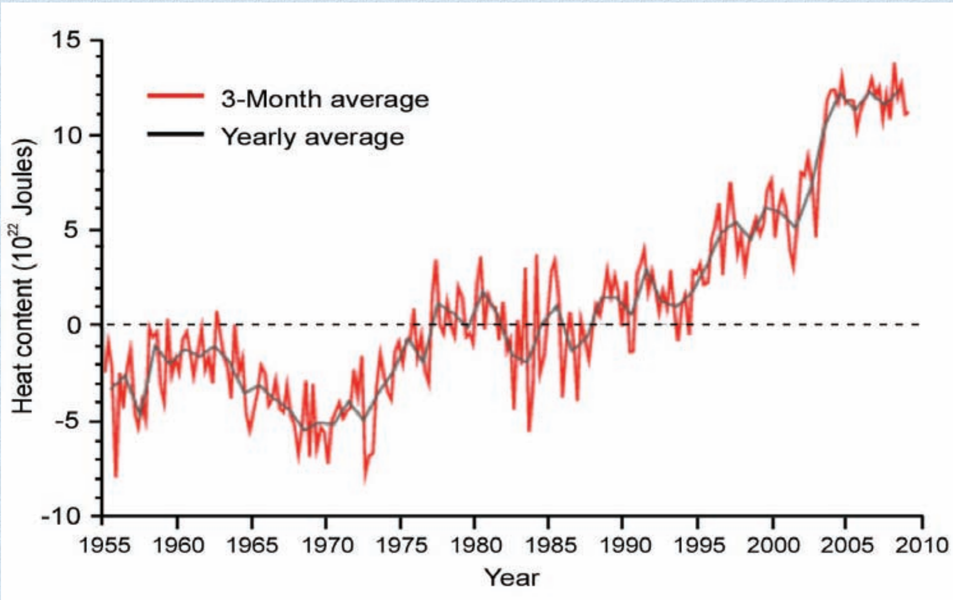
- Because surface currents transport large amounts of heat from the tropics to subpolar latitudes, understanding their trends and variability is critical to prediction of SST anomalies. Indeed, surface current anomalies have been observed to lead SST anomalies, and therefore serve as early indicators of phase shifts in El Niño, and perhaps other climate cycles.

- Observations of surface currents are essential for evaluation of parameterized processes, or phenomena such as wind-driven currents and spatial patterns of seasonal circulation, in coupled ocean-atmosphere climate models.

- Knowledge of surface currents is also essential to computation of dispersal of ocean pollutants, enhancement of fishery models, and improvement of air-sea rescue operations.

Ocean Heat Content and Transport – Observed to better understand the extent to which the ocean sequesters heat, to identify where heat enters the ocean and where it re-emerges to interact with the atmosphere, and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change.

- Heat absorbed by the ocean raises ocean temperatures, in particular SSTs.



Time series of seasonal and annual mean Ocean Heat Content (10^{22} Joules) for the upper 700 m of the world ocean. The observed increase in ocean heat content for the past fifty years accounts for more than 80% of the warming of the Earth system that has occurred during this period. This increase is consistent with the increase expected due to the observed increase of greenhouse gases in the Earth's atmosphere. (http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/)

- The ocean is by far the Earth's greatest reservoir for heat that accumulates as a result of the planetary energy imbalance caused by greenhouse warming. The large thermal inertia of the ocean delays the impacts of greenhouse warming, which, on the one hand presents society with an opportunity to mitigate climate change, and on the other hand commits the Earth to ongoing warming for decades to come.

- Quantifying heat sequestration via measurement of ocean temperature is, therefore, critical to predicting global temperature rise attributable to greenhouse gas emissions, and, therefore, the magnitude of emissions reductions necessary to stabilize climate.

- Increased storage of heat leads to thermal expansion of water and to local increases in air temperatures that may accelerate the melting of land-based ice, causing an increase in sea level with profound impacts on coastal communities and ecosystems.

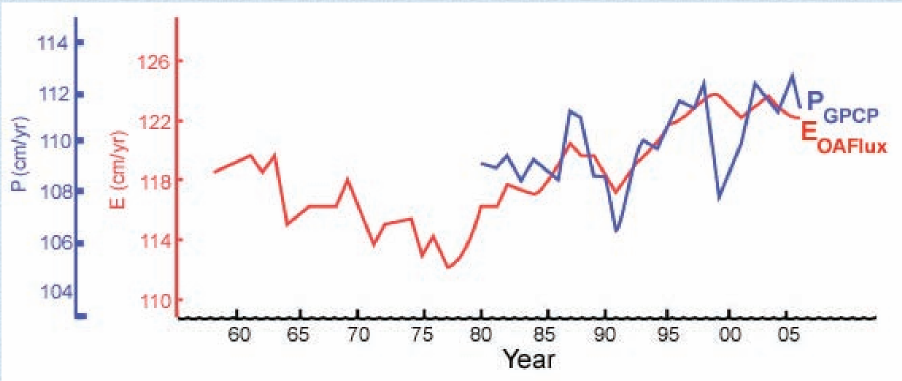
- The ocean absorbs and stores heat at the surface and releases it to the atmosphere in remote locations, thereby contributing substantially to climate variability. The wind-driven large-scale circulation of the upper layers of the ocean moves heat, salt and freshwater around the globe, thereby influencing SSTs, weather patterns, regional climate phenomena, and local sea level elevations; transport of heat between the eastern and western tropical Pacific Ocean, for example, is a critical feature of El Niño and La Niña, which profoundly impact temperature and precipitation patterns in equatorial regions. At high latitudes, cooling of salty surface waters causes them to sink to great depths where they form massive subsurface currents; the meridional overturning circulation, commonly referred to as the ocean conveyor belt, redistributes large quantities of heat in patterns that, for example, make Europe habitable.

- Tropical cyclones derive energy from the ocean, and their intensification is related to the heat content of the upper layers of the ocean directly beneath the storm tracks.

Air-Sea Exchanges of Heat, Momentum, and Freshwater – Observed to identify changes in forcing functions driving ocean conditions and atmospheric conditions, and to elucidate oceanic influences on the global water cycle.

- The ocean, which stores the bulk of the sun's energy absorbed by the planet, communicates with the atmosphere via exchanges across the ocean surface.

- Ocean-atmosphere exchange of heat, water and momentum drive the circulation of the ocean, which redistributes heat (e.g., from the tropics to the poles), thereby influencing global and regional climate. Ocean-atmosphere exchange of heat and freshwater alters the density of the surface water; cooling of the ocean makes the ocean denser, evaporation makes the ocean saltier and, hence, denser, while heating of the ocean and precipitation have the opposite effect. These air-sea exchanges start a cascade of phenomena in which dense surface water sinks thereby feeding the large-scale meridional overturning circulation. On the other hand, surface winds distort the sea surface and drive the large-scale upper ocean circulation, which also transports heat and freshwater. Surface water blown away from the shore in coastal regions causes upwelling of nutrients that influences fisheries.



Time series of globally averaged evaporation and precipitation over the ocean. The figure shows the time series of annual-mean global ocean evaporation, for the period 1958-2006, produced by the WHOI OAFlux (Objectively Analyzed air-sea Fluxes) project, superimposed on the annual-mean time series of global ocean precipitation, for the period 1980-2006, from the NASA GPCP (Global Precipitation Climatology Project). OAFlux combines in situ ocean observations with remote sensing from multiple satellites and surface meteorology from numerical weather prediction reanalysis (http://oaflux.whoi.edu/). GPCP combines remote observations from multiple microwave and infrared satellite sensors (http://precip.gsfc.nasa.gov). Ocean evaporation has been increasing since the late 1970s with the largest rate of change in the 1990s, the period in which global warming was particularly pronounced. Evaporation drives the global hydrological cycle. The coherent upward trends in OAFlux evaporation and GPCP precipitation provide observational evidence suggesting an acceleration of the global hydrological cycle associated with global warming. Figure courtesy of Lisan Yu, Woods Hole Oceanographic Institution (WHOI).

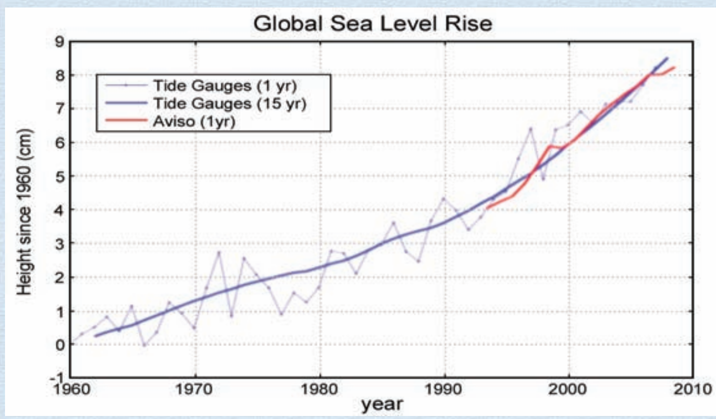
(2) when land-based glaciers, snow and ice melt they add water to the ocean.

- By independently evaluating changes in the mass of the ocean, globally averaged sea level rise provides a sensitive measure of how much heat, as a consequence of greenhouse warming, is sequestered in the ocean.
- Sea level rise differs greatly from region to region because of differences in local land rise or subsidence; geographically differing ocean currents that influence how much water is piled up against coastlines; and variations in ocean heat content, salinity, atmospheric pressures, winds and currents that occur as a consequence of natural variability (for example, El Niño).
- Rising sea levels have profound impacts on coastal communities and ecosystems via gradual inundation of low lying areas that causes flooding and erosion, intrusion of salty waters into freshwater systems, and damage due to enhanced storm surges.

- Heat taken up by the ocean surface layer in the summer is released back to the atmosphere in the winter; evaporation cools the ocean and warms the atmosphere (via subsequent heat release caused by condensation to precipitable liquid water), with the net effect of mitigating seasonal extremes in atmospheric temperature.
- Evaporation over the ocean exceeds precipitation over the ocean, resulting in net transport of moisture to land. As the ocean warms, the hydrological cycle is expected to intensify, with consequences for rain and snowfall over land. Via this mechanism, the oceans capture large amounts of the sun's energy and transfer it to land.
- Ocean-atmosphere exchange of carbon dioxide by diffusion across the ocean surface results in ocean uptake of between a third and a half of all anthropogenic CO_2 emissions.

Sea Level – Observed to identify changes resulting from trends and variability in climate.

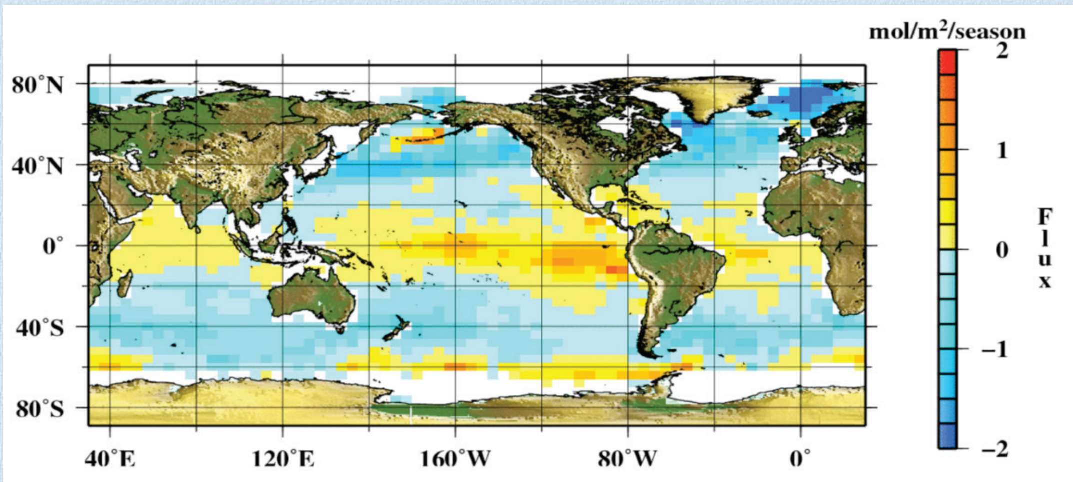
- Sea level rise is both an impact and a diagnostic of the Earth's energy imbalance caused by greenhouse warming. Sustained observations are required to elucidate the variability and trends of sea level rise and their causes.
- Sea level rises in a warming climate for two primary reasons: (1) when seawater warms it expands, and



Accelerating global average sea level rise. The global average trend has risen from under 2 mm/year rise over the past 50 years, inferred from tide gauge records, to over 3 mm/year rise over the past 15 years, observed by both tide gauges and satellite altimetry. In situ tide gauge measurements are required to calibrate the space-based altimeters that provide global coverage. Absolute sea level is changing at different rates around the world, with local trends relative to coasts, which separately rise or subside, varying from about +10 mm/year to about -10 mm/year. Figure courtesy of Mark Merrifield, University of Hawaii Sea Level Center.(For AVISO satellite altimetry see www.aviso.oceanobs.com. See, also, http://sealevel.colorado.edu.)

Ocean Carbon Uptake and Content – Observed to better understand the extent to which the ocean sequesters CO_2 and how cycling among carbon reservoirs varies on seasonal-to-decadal time scales.

- Ocean-atmosphere exchange of CO_2 by diffusion across the ocean surface results in ocean uptake of between a third and a half of all anthropogenic CO_2 emissions. As such, the ocean constitutes the largest single sink for the greenhouse gas most responsible for global climate change.



The global pattern of the net air-sea CO_2 flux for September-December 2007, inferred from in situ measurements of CO_2 partial pressure and sea surface temperature and wind speeds derived from satellite and data assimilation model products. Negative fluxes represent uptake of CO_2 by the ocean. The map shows the characteristic global pattern of net release of CO_2 in the tropics and regions of upwelling, and uptake of CO_2 at mid- and high latitudes. (http://lwf.ncdc.noaa.gov/oa/ climate/research/2008/ann/bams/)

- Air-sea exchange of CO_2 is a sensitive function of temperature, wind speed, sea surface roughness, ocean vertical mixing, precipitation, and local biological activity in the ocean. As a consequence, ocean uptake of CO_2 varies greatly with season and location; indeed, some regions of the ocean are net sources while others are net sinks of CO_2. Observations are required to identify these regions and the ocean processes that control their behavior.

- Large-scale patterns of natural climate variability, such as El Niño, are known to significantly alter regional air-sea exchange of CO_2.

- In order to project the future capacity of the ocean to sequester anthropogenic CO_2 emissions it is necessary to elucidate the processes that influence air-sea exchange rates and to better understand how those processes might vary as the Earth's climate changes.

- A consequence of ocean uptake of CO_2 is acidification of the ocean, with potentially significant impacts on marine biota.

Sea Ice Thickness and Extent - Observed to elucidate climate variability and rapidly changing climate change at high latitudes.

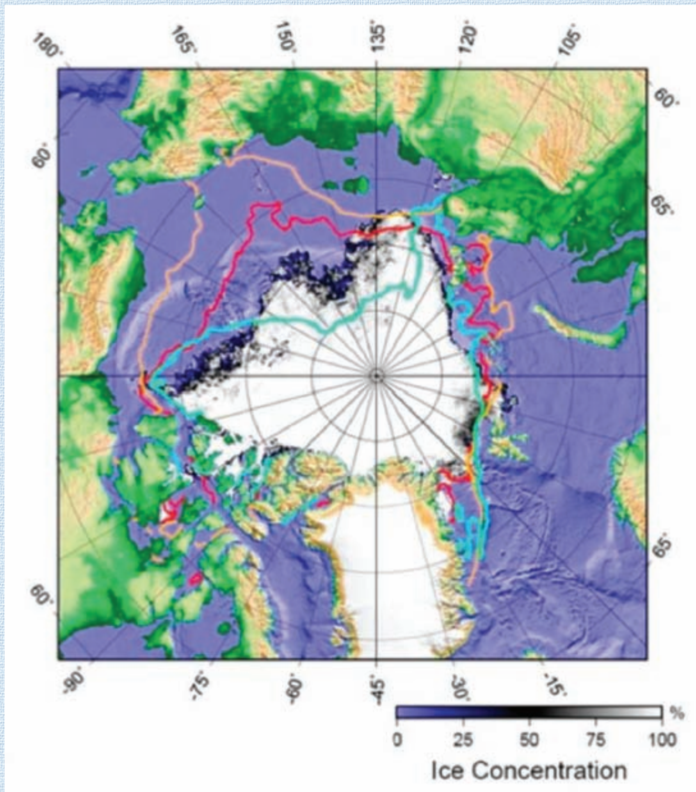
- The Arctic region is warming at a rate twice that of the planet as a whole; loss of sea ice is a sensitive indicator of global climate change.

- Melting of sea ice results in darker ocean and land surfaces that reflect less and absorb more sunlight, resulting in enhanced absorption of energy by the Earth. This increased warming melts yet more ice, thus providing a self-amplifying feedback loop that leads to further increases in global warming.

- Melting sea ice adds freshwater to the ocean. By diminishing the salinity (hence, density) of the surface water, this may slow the ocean circulation that brings heat from the tropics to the poles, thereby affecting global and regional climate. It is noteworthy, in this regard, that melting of continental ice sheets in Greenland occurs in a particularly sensitive region of deep-water formation.

- Sea ice caps the ocean and interferes with ocean-atmosphere exchange of heat, moisture, and gases. Melting of Arctic sea ice results in increased fluxes of heat and moisture from the surface to the atmosphere, with potential to substantially influence Northern Hemisphere atmospheric circulation patterns and, hence, Northern Hemisphere weather and precipitation. For example, anomalously low summer ice cover may influence the North Atlantic Oscillation (NAO) during the subsequent autumn and winter, with potentially significant impacts on global climate.

- Reductions in sea ice and increasing Arctic SSTs strongly impact animals such as polar bears and seals, fisheries, and indigenous human communities.



Variation in Arctic sea ice cover from the mean September 1979-1983 range (orange), to the mean September 2002-2006 range (red), to the ice extent minimum in 2007 (blue). The extent of September sea ice cover in 2008 (shown in white) is depicted by the satellite imagery from the Advanced Microwave Scanning Radiometer (AMSR). The September rate of sea ice decline since 1979 has now increased to 11.2 percent per decade. (See www.ifm.zmaw.de/forschung/fernerkundung/meereis/amsre-sea-ice)

The In Situ Observing System

NOAA is the world leader in implementing the in situ elements of the global ocean observing system for climate. The NOAA Climate Observation Division sponsors the majority of the global component of the U.S. Integrated Ocean Observing System (IOOS)[3].

A global observing system by definition crosses international and institutional boundaries, with benefits and responsibilities shared by many. A central precept of NOAA's ocean climate observation strategy, therefore, is to work in partnership with other nations and other agencies.

Accordingly, all of NOAA's contributions to global ocean observation are coordinated internationally in cooperation with the Joint World Meteorological Organization - Intergovernmental Oceanographic Commission (WMO/IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM). The observing system is implemented in accordance with the international Global Climate Observing System (of the World Meteorological Organization) *Implementation Plan for the Global Observing System for Climate in support of the UNFCCC* (GCOS-92)[4].

The Observational Subsystems

The Climate Observation Division manages implementation of the NOAA contribution to the global ocean observing system as a set of observational networks or subsystems. Each subsystem brings unique strengths and limitations; together they build the whole; they are interdependent and function synergistically, providing stand-alone datasets and analyses, and supplying the observational infrastructure that underlies national and international climate research and operational activities.

Currently, over 8,000 observational[5] platforms are deployed throughout the global ocean, with plans to increase that number to bring the system into compliance with the initial GCOS design. NOAA sponsors nearly half of the platforms presently deployed in the global ocean, with over 70 other countries providing the remainder.

Implementation of the U.S. observational networks is accomplished by NOAA entities, laboratories, and university-based Cooperative Institutes, working in close partnership with each other under funding from the Climate Observation Division. Satellites also provide critical contributions to global ocean observation, but operation of the satellites does not fall under the mandate of the Climate Observation Division.

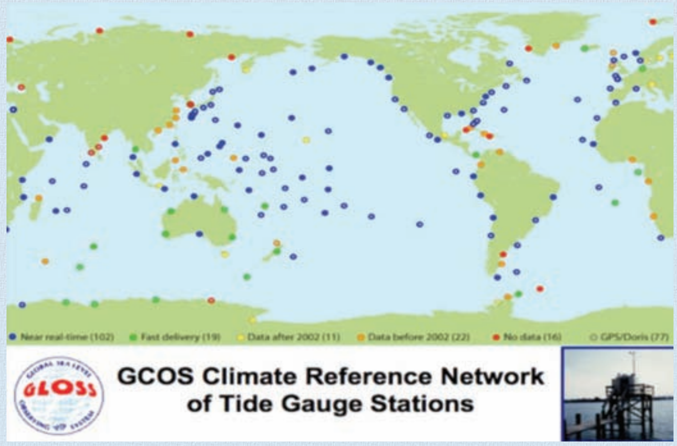
[3] These in situ observations also map to other organizational efforts, serving as the U.S. contribution to the international Global Ocean Observing System (GOOS), and the ocean baseline of the Global Earth Observation System of Systems (GEOSS).

[4] The GCOS-92 plan has been endorsed by the United Nations Framework Convention on Climate Change (UNFCCC) and by the Group on Earth Observations (GEO).

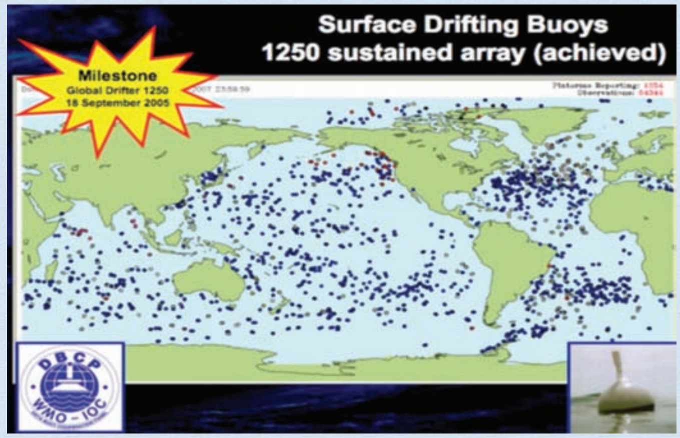
[5] Despite the magnitude of the system, coverage of the ocean remains sparse. Even 10,000 platforms distributed over the global ocean would average to only one observational station in an area three times the size of metropolitan Los Angeles.

Tide Gauges

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



Tide Gauge Stations. The task is to upgrade all 170 stations to measure relative land motion and to report in near real-time (blue icons).



Surface Drifting Buoy Array. A major milestone was reached in September 2005 when the global drifter array achieved its initial design goal of 1,250 data buoys in sustained service, and became the first component of the Global Ocean Observing System to be fully deployed.

are assimilated into global climate models for predicting climate variability and change. Older tide stations are being upgraded with modern technology, particularly in less developed countries. Permanent GPS receivers are being installed at select stations, with the goal of deploying a geocentrically located subset of 170 GCOS Climate Reference Stations. These Climate Reference Stations are also being upgraded for real-time reporting, not only for climate monitoring purposes, but also to support marine hazard warning (e.g., tsunami warning).

The global sea level network provides one of the best examples of the international partnerships critical to climate observation. NOAA supports tide gauge station operations in over 30 countries and collects near real-time data from over 100 stations worldwide. The multi-national system is coordinated through the JCOMM Global Sea Level Observing System (GLOSS) Group of Experts. Near real-time data are distributed by the GLOSS data assembly center operated at the University of Hawaii, and historical data are archived and distributed by the NOAA National Oceanographic Data Center.

Surface Drifting Buoys

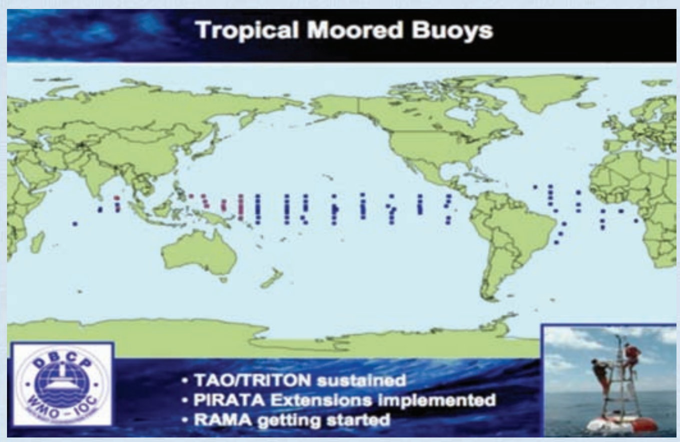
Global sea surface temperature analyses are derived from satellite retrievals, but the satellite measurements must be continuously calibrated using surface in situ measurements. The design for the global surface drifting buoy array (GCOS-92) calls for 1,250 buoys to be maintained world-wide, spaced approximately 500 km apart in order to adequately tune satellite 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. Drifters equipped with barometers provide critical near real-time observations of atmospheric pressure for numerical weather prediction, as well as for documenting global-scale trends in climate variability. The drifters report hourly via satellite communications. Specially equipped "hurricane drifters" are now routinely air-dropped in the path of hurricanes approaching the U.S. coast in order to improve hurricane intensity and landfall predictions. NOAA, together with international partners, is working to augment the drifter array with subsets of buoys for wind, pressure, salinity, and temperature profile measurement capabilities.

The global drifting buoy array reached its initial design goal of 1,250 data buoys in sustained service in 2005. The next challenge is to equip all buoys with barometers, and to install salinity sensors on a subset of 300 buoys, particularly in the sub-polar regions for analysis of freshwater input from melting ice sheets and changes in thermohaline circulation.

The NOAA global drifter program is managed in close cooperation with about a dozen other countries that contribute to this subsystem under the framework of the JCOMM Data Buoy Cooperation Panel. Near real-time data are compiled at the Global Drifter Program Data Assembly Center at the NOAA Atlantic Oceanographic and Meteorological Laboratory, and historical data are archived and distributed by the Canadian Integrated Science and Data Management program.

Tropical Moored Buoy Network

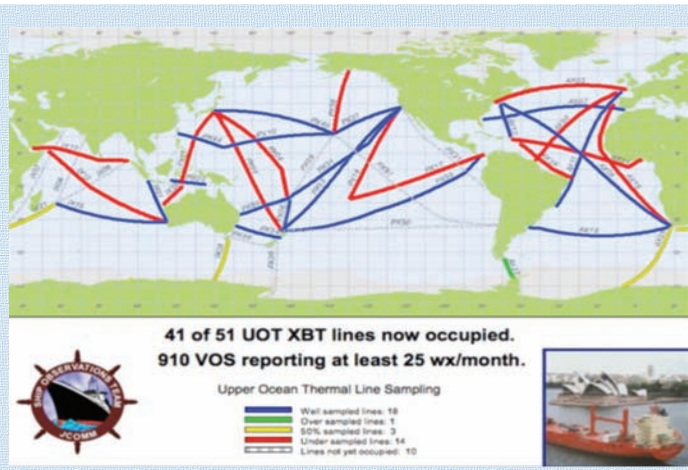
Most of the heat from the sun enters the ocean in the tropical/sub-tropical belt. Past understanding of the role of the tropics in forcing mid-latitude weather and climate has been garnered through the observations of the tropical moored buoy array in the Pacific Ocean, TAO/TRITON (Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network), which now comprises 67 moorings. A similar array of 17 surface moorings in the Atlantic basin, PIRATA (Pilot Research Moored Array in the Tropical Atlantic) is further improving forecasting capabilities and is elucidating causes of longer-term changes in the ocean. The next challenge is to advance the tropical moored array across the Indian Ocean, in cooperation with international partners. The Indian Ocean array, RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction), whose system design calls for 46 moorings, will complete global



Tropical Moored Buoy Network. The Tropical Moored Buoy Network extends across 3 ocean basins, with 67 TAO/TRITON buoys in the Pacific, 17 PIRATA buoys in the Atlantic, and 43 planned (8 current) RAMA buoys in the Indian Ocean.

coverage of the Earth's tropical oceans. In addition to monitoring the air-sea exchange of heat and water, the moored buoys provide platforms for instrumentation to measure the air-sea exchange of carbon dioxide in the tropics.

The TAO/TRITON array in the Pacific Ocean is operated (under separate management, by the NOAA National Data Buoy Center) in cooperation with Japan; the PIRATA array in the Atlantic is operated by NOAA in cooperation with Brazil and France; the RAMA array in the Indian Ocean is operated by NOAA in cooperation with Japan, France, India, Indonesia, China, and a consortium of nine African nations participating in the Agulhas and Somali Current Large Marine Ecosystem Project. Near real-time data are available for TAO/TRITON from the NOAA National Data Buoy Center, and for PIRATA and RAMA from the NOAA Pacific Marine Environmental Laboratory. Historical data are archived and distributed by the NOAA National Oceanographic Data Center and the NOAA National Climatic Data Center.



Ships of Opportunity deploy Expendable Bathythermographs (XBTs) to measure sub-surface temperature profiles on trans-oceanic routes. A larger fleet of Volunteer Observing Ships reports weather observations that are used for weather nowcasting and forecasting, analysis of sea surface temperatures, and analysis of climate-scale trends over the global ocean.

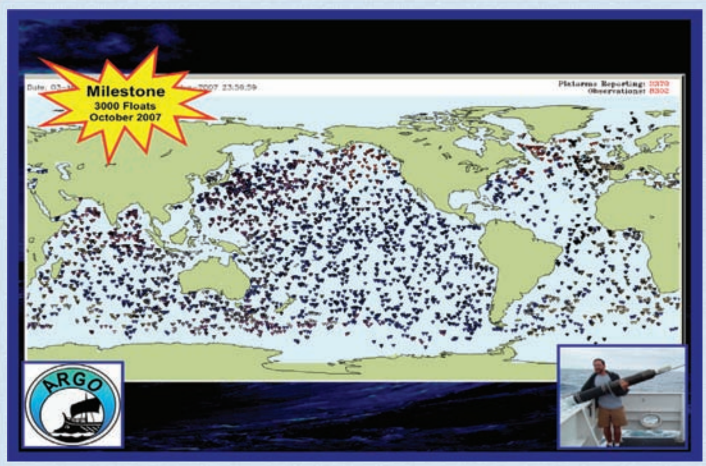
Ships of Opportunity

The global atmospheric and oceanic data from the Ships of Opportunity Program (SOOP) provide the foundation for understanding long-term changes in marine climate. The ships of opportunity are commercial carriers that transit scientifically important trans-oceanic routes; they volunteer to take ocean measurements using NOAA-supplied instruments, or host NOAA technicians on board during the transits to take the measurements. NOAA is concentrating on a subset of 51 high accuracy SOOP lines to be frequently repeated and sampled at high resolution for systematic upper ocean temperatures (using Expendable Bathythermograph probes – XBTs) and atmospheric variables. These lines provide highly accurate measurements of the upper ocean thermal structure, sea surface temperature, air-sea exchange of carbon dioxide, and surface meteorology, with a focus on enhancing data quality through improved instrument accuracy, automated reporting, and better records of how the observations are taken. Additionally, the SOOP fleet is a primary vehicle for deployment of the arrays of surface drifting buoys and Argo profiling floats. Over two dozen countries contribute to the operation of this subsystem, which is coordinated through JCOMM. Data are archived and distributed by the NOAA National Oceanographic Data Center.

Closely aligned with the Ships of Opportunity Program is the Volunteer Observing Ship (VOS) program, which is separately managed in the U.S. by the NOAA National Data Buoy Center. This network is maintained primarily for weather observations at sea, but, since ships have been recording weather observations for over 150 years, the observational data are used extensively for climate studies as well, particularly for assessment of long-term trends. All maritime nations participate. There are about 900 VOS that report regularly; data from about half of those are processed by NOAA. A subset of 250 ships is targeted by JCOMM for registry in the Volunteer Observing Ship Climate Project to provide enhanced data reports for climate observation. Data are archived and disseminated by the NOAA National Climatic Data Center.

Argo Profiling Floats

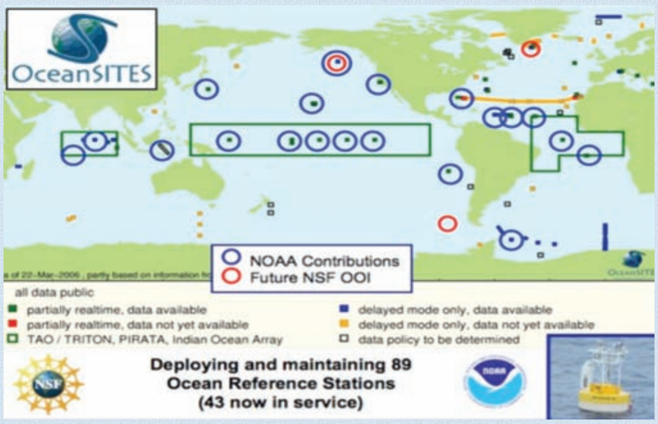
The heat content of the world's oceans and the transfer of that heat to and from the atmosphere are variables central to the climate system and are directly responsible for influencing worldwide sea levels. The Argo array of profiling floats, which measures temperature and salinity down to 2000 meters below the ocean surface, provides broad-scale, basin-wide monitoring of the upper ocean heat content. The initial goal of three thousand floats in active service was achieved in October 2007; the U.S. contribution is approximately one-half of this total. Glider technology is now being developed to augment standard drifting Argo floats in the boundary currents and in targeted deep circulation regions, where station-keeping by standard floats is not possible. The measurements from the Argo array have demonstrated the need for climate observations below 2000 meters in depth in order to measure the total global heat storage in the ocean; designing and building deep diving floats is a critical



Argo array of Profiling Floats. A major milestone was reached in October 2007 when the Argo array achieved its initial design goal of 3000 active floats deployed.

technology challenge, as is expanding measurements to better sample the marginal seas.

Over twenty countries and the European Union contribute to the international Argo program. The U.S. component is implemented by NOAA. Near real-time data are maintained and distributed by the Argo Global Data Assembly Centers at the Navy Fleet Numerical Meteorology and Oceanography Center in Monterey, California and the French Research Institute for Exploitation of the Sea in Brest, France. Historical data are archived and distributed by the NOAA National Oceanographic Data Center.



Ocean Reference Stations. The multi-disciplinary OceanSITES reference station plan calls for 89 flux moorings, transport stations and observatories, with 43 presently in operation.

Ocean Reference Stations

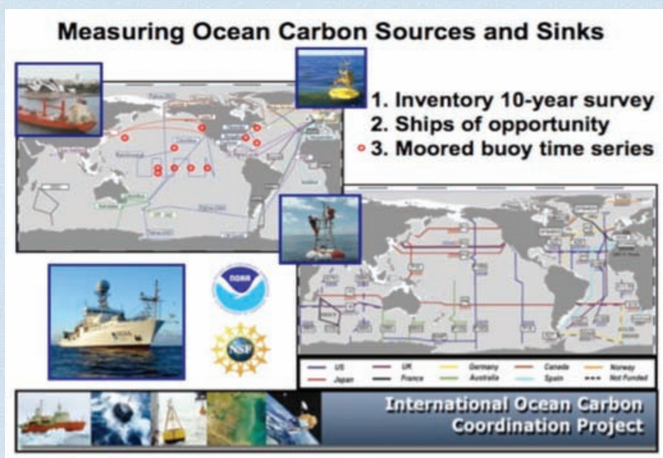
Sustained time-series of oceanic and atmospheric climate-relevant parameters and air-sea exchange of heat, freshwater and carbon dioxide are central to documenting and understanding trends and variability in the climate system. To this end NOAA, together with international partners, is implementing a global network of ocean reference station moored buoys to provide the most accurate long-term climate data records of oceanic and near-surface atmospheric parameters in key ocean regimes. The National Science Foundation's Ocean Observatories Initiative will provide a major piece of the infrastructure needed for this network, establishing high-capability moored stations, particularly in high latitude ocean locations. NOAA's contribution includes the tropical regions where a subset of the TAO/TRITON, PIRATA, and RAMA networks are being upgraded to reference station quality, as well as several other long time-series sites focused on measurement of air-sea fluxes. Additional long-term monitoring to measure the primary routes of ocean transport is sustained at key choke points such as the Indonesian through-flow, while continental boundary currents such as the California Current are observed to monitor changing climate regimes that strongly impact fisheries and ecosystems.

Sustained observations are also necessary to document trends and variability in the ocean's overturning circulation to elucidate the role of the ocean in rapid climate change. Consequently, the ocean observing system maintains watch at a few control points at critical locations. Long-term measurements from bottom-mounted and subsurface moored arrays, and repeated temperature, salinity, and tracer surveys from research vessels form the backbone of this network.

The Ocean Reference Station global effort is coordinated by the JCOMM-affiliated OceanSITES program, and is one of the most challenging networks to implement because of the expense of maintaining highly accurate instruments in remote ocean regions. Yet this network is essential for evaluation of climate model outputs. The system design calls for 87 stations, of which about half are presently in operation. Global data assembly centers are maintained at the NOAA National Data Buoy Center and the French Research Institute for Exploitation of the Sea.

Ocean Carbon Networks

Projections of global climate change are closely linked to assumptions about the interactions among the atmosphere, land, and ocean that control levels of atmospheric carbon dioxide. Accordingly, deriving an understanding of the global carbon cycle from accurate measurements of the regional sources and sinks of carbon is of critical importance to national and international decision- and policymaking. Because the ocean is both a large reservoir and sink for carbon dioxide, ocean measurements are critical to quantifying how carbon cycles through the global climate system, and, hence, to understanding present atmospheric carbon levels and to projecting future levels against a backdrop of changing climate. To this end, NOAA deploys carbon dioxide sampling on moored arrays and on Ships of Opportunity to analyze the seasonal variability of carbon exchange between the ocean and atmosphere. Additionally, in partnership with NSF, NOAA participates in systematic global ocean surveys that provide a comprehensive ocean carbon inventory once every ten years.



Ocean Carbon Networks. Air-sea exchange of carbon dioxide is measured continuously on ships of opportunity and moored buoys, while deep-sea storage of carbon is measured in a series of transects designed to survey the global oceans on a decadal time scale.

The ships used to conduct the carbon inventory survey sample the complete ocean water column from top to bottom, not only for carbon but for temperature, salinity and tracers as well. These observations are also essential to calibrate the measurements from the Argo array and to document changes in the deep ocean beyond the reach of present Argo float technology.

Over a dozen countries contribute cooperatively to ocean carbon observations under the umbrella of the International Ocean Carbon Coordination Project. All U.S. and many European and other ocean carbon datasets are archived at the Department of Energy Carbon Dioxide Information Analysis Center and the National Science Foundation CLIVAR and CO2 Hydrographic Data Office.

Suggested Arctic Ocean Observing System, as proposed by SEARCH (The Study of Environmental Arctic Change), 2005 Implementation Workshop.

Arctic Observing Network

Climate change is occurring rapidly in the Arctic, whose environment is particularly sensitive to climate variability and change. Therefore, a high priority program of sustained Arctic observations is being conducted utilizing ship-based cruises, permanent oceanographic moorings, gliders, ice beacons and buoys, supplemented by acquisition and analysis of historical and satellite-based data sets. Observational goals include detection of climate-driven physical and ecological change, especially due to changes in long-term and seasonal sea ice extent and duration, as well as alterations in ocean density and circulation that together may lead to changes in global ocean heat and freshwater transport, productivity, food web structure, and biodiversity.

Over the past 20 or more years, NOAA has collaborated with other U.S. agencies to deploy sea ice beacons and ice mass balance buoys. Data reported through the National Ice Center provide an essential contribution to the International Arctic Buoy Programme, tracking changes in the sea ice extent, thickness and age, as well as providing pressure and temperature observations for numerical weather prediction. NOAA is also working with NSF and international partners via the Arctic Council, to develop implementation plans for a Sustained Arctic Observing Network (SAON). NOAA will provide the programmatic focus within the United States for maintaining the SAON over the long term.

Since 2004 NOAA and the Russian Academy of Sciences have led the Russian-American Long-term Census of the Arctic (RUSALCA). The goals of this program are to monitor the fluxes of freshwater, heat and nutrients from the Pacific Ocean through the Bering Strait, which, in turn, influence outflow into the North Atlantic. Multiple moorings are maintained, and every four to five years the U.S. and Russia lead a multi-disciplinary census of the ecosystem and ocean-sea ice changes in this region.

Dedicated Ships

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 fully characterize climate change. Accordingly, research vessel and dedicated ship support from the NOAA and the University-National Oceanographic Laboratory System (UNOLS) fleet is an essential component of the global climate observing system, providing the infrastructure necessary for deployment of the moored and drifting arrays, and for performing deep ocean surveys. In addition to providing the survey and deployment platforms for the autonomous arrays, the research fleet maintains sensor suites on a small core of vessels as the highest quality calibration points for validation of the other system measurements.

This work is supported by the NOAA Office of Marine and

NOAA Ship RV Ronald H. Brown.

Aviation Operations. The Climate Observation Division provides supplemental funding to support NOAA and UNOLS ship time and cooperative projects with other countries.

Data Management, Analysis and Product Delivery

Timely retrieval of ocean-based measurements greatly enhances their value. Data from buoys and floats are transmitted in real-time via NOAA and other satellites to shore-side processing centers, are compiled and quality controlled at data assembly centers, and are archived and redistributed by national and international data centers. Data management is a requisite component of all the observational subsystems.

The observing system starts, but does not end, with ocean-based measurements and their retrieval. The utility of the measurements rests upon their accessibility by the broad climate and oceanographic communities, and upon derivation of climate-related information from raw ocean data. Accordingly, the observing system sets standards and requirements for archiving of ocean data and metadata. Key data centers are located at the NOAA National Oceanographic Data Center and at the NOAA National Data Buoy Center. Monitoring of the observing system is done in concert with national and international partners at the NOAA Observing System Monitoring Center, the JCOMM in situ Observing Programme Support Centre (JCOMMOPS), and the Global Observing Systems Information Center. The observing program also participates, in coordination with the NOAA Integrated Ocean Observing System, in development of a robust data management and communications system, for retrieval of data from widely dispersed sources. In addition, data management and communications are coordinated internationally in accordance with World Meteorological Organization's WMO systems and standards.

Once retrieved, data fields are combined in analyses that document what the ocean and atmosphere are doing at present and what they did in the past, thus providing a record of the changing and variable climate. Representative examples of analyses routinely provided by the observing system include creation of global maps of sea surface temperatures, and evaluation of ocean heat content, sea surface currents, deep ocean circulation, global and regional sea level, air-sea exchanges of heat and carbon dioxide, and oceanic evaporation and precipitation.

For climate forecasting purposes, data from many different observational networks are combined in models. To this end, the observing system supports development and implementation of data assimilation systems. Model applications based upon ocean observations include ocean initialization of seasonal climate forecasts and decadal forecasts of ocean heat uptake, thermohaline circulation, and changes in oceanic carbon sources and sinks. By routinely comparing models and data, shortcomings in the observing system can be identified and both the models and forecasts can be improved.

Integrated Ocean Observations in Service of Society

Variability and change in ocean properties – including sea surface temperature and currents; heat content and transport; air-sea exchange of heat, freshwater, and carbon dioxide; sea level; and sea ice thickness and extent – modulate the Earth's climate and its impact on human society. Water resources are impacted in the short term by El Niño and in the long term by droughts that respond to ocean temperatures; coastal inundation reflects sea level rise; health of fisheries responds to changes in ocean circulation, temperature, and nutrients; intensification of hurricanes reflects ocean warming. Understanding and predicting these and many other phenomena require sustained and comprehensive observations of the state of the ocean.

The international Global Climate Observing System Implementation Plan for the Global Observing System for Climate in support of the UNFCCC (GCOS-92) specifies a broad set of Essential Climate Variables, observation of which would begin to meet society's needs for climate information. Working in concert, the collection of observational subsystems deployed by NOAA and its international partners constitute the global ocean observing system that is being implemented in response to those needs. The data acquired by the observing system, which are readily available to all, provide the observational backbone underlying characterization of the trends and variability in the Earth's climate. These data also support worldwide research studies designed to better understand and model the workings of the climate system, experimental and operational forecasts of future climate, and development of targeted products and services to better inform society about the impacts and options for responding to climate-related phenomena. The successful design, development, deployment and maintenance of the many interlocking components required to bring the global integrated ocean observing system to fruition is a testament to the sustained and dedicated efforts of hundreds of scientists, engineers, technicians, students, sailors, support staff, administrators and managers working cooperatively at dozens of institutions worldwide. We are proud to present the U.S. contributions to this observing system.

The Climate Observation Division can be contacted at climate.observation@noaa.gov.