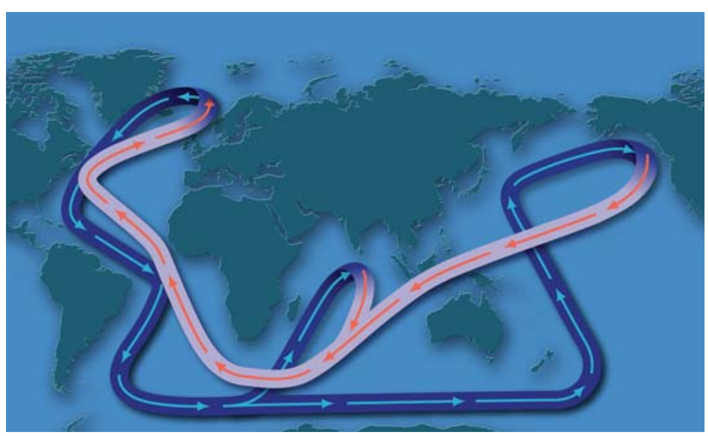
Sea

Ocean covers roughly 71 percent of Earth's surface and hosts some of its most productive ecosystems. Sea currents and surface temperature drive weather patterns and create the climate. Evaporation from the sea surface accounts for most of the precipitation that falls on Earth. The ocean's ability to absorb and store energy allows it to serve as a buffer against extreme climatic swings. And, importantly, the ocean has an enormous capacity to remove carbon dioxide (CO_2) from the atmosphere; researchers estimate that the oceans have absorbed roughly one-third of the anthropogenic carbon released into the air.

NSF-supported researchers have long sought accurate models of the properties and circulation of Earth's ocean because of the important role ocean circulation plays in our planet's climate. Researchers now know that the sea is as essential to a global climate model (such as the NSF-supported Community Climate System Model (CCSM)) as the atmosphere itself. In recent decades, researchers have demonstrated that the ocean plays a critical role in transporting energy around the world, so much so that some have called it the "global heat engine."[1]

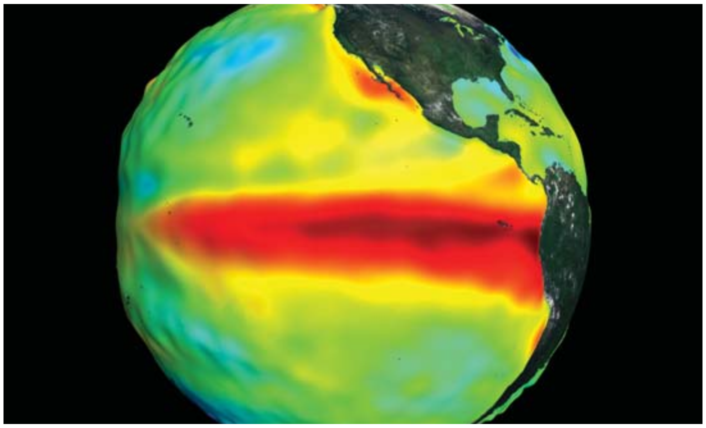


The global ocean circulation system, often called the "ocean conveyor," transports heat throughout the planet. Light sections represent warm surface currents. Dark sections represent deep, cold currents. *Credit: Illustration by Jayne Doucette, Woods Hole Oceanographic Institution*

Heat stored in the ocean warms the atmosphere, as evidenced by the temperate climates of coastal regions compared with the larger temperature swings of inland areas at the same latitudes. The temperature gradients in the atmosphere caused by heat transfer from the ocean influence wind patterns. Wind-driven waves, which transfer energy from the atmosphere to the ocean, are a driving

1 NASA Facts: The Roles of the Ocean in Climate Change, 1999: http://earthobservatory.nasa.gov/Newsroom/MediaResources/Roles_Ocean.htm

Top image credit: © 2009 Digital Vision, Gety Images force behind ocean current patterns. Temperature and salinity are the key variables affecting seawater density and drive vertical ocean circulation; density increases with increasing salinity or decreasing temperature. Colder, saltier water is denser than warmer, fresher water, and sinks to lower depths.[1]



The 1997–1998 El Niño event affected weather patterns around the world. El Niño years are characterized by an unusual extension of warm water across the Pacific Ocean, illustrated in shades of red in the image above. *Credit: NASA/Goddard Space Flight Center; The SeaWiFS Project; ORBIMAGE Science Visualization Studio*

The warming or cooling of the ocean's surface can have far-reaching effects on the atmosphere. For example, the El Niño phenomenon is associated with warmer water extending farther than normal across the tropical Pacific Ocean.[2] Researchers use the CCSM and other global climate models to predict El Niño events, which can have profound impacts on human activities.

Unraveling the role of the ocean in the cycling of carbon in the Earth system has been a challenge for NSF researchers. The ocean contains about 50 times as much CO_2 as the atmosphere. Even slight changes in the marine carbon cycle can substantially influence the amount of CO_2 contributing to the greenhouse effect in the atmosphere. Researchers have found evidence that the marine carbon cycle was a significant factor in transitions to and from past ice ages.[3] Modelers need to know how much anthropogenic carbon the ocean can absorb. Ecologists and oceanographers seek to understand how this absorption will affect ocean ecosystems and chemistry, and the sustainability of essential ecosystem services of the sea.

As the amount of dissolved CO_2 increases in the ocean, its acidity also increases.[4] NSF-funded researchers have found that increased acidity changes the chemical balance of the ocean, causing potentially significant disruptions in ecosystems, particularly for species that build shells or exoskeletons, such as phytoplankton, shellfish, and coral. Because phytoplankton form the foundation of the food chain and coral reefs provide important habitats, ocean acidification could have a dramatic effect on the entire ocean system. Colder seas, including polar ecosystems, which host some of the most economically important fisheries in the world, are particularly vulnerable to ocean acidification because cold water can dissolve more CO_2 than warmer water.[5]

The first buoy to monitor ocean acidification, a result of carbon dioxide absorbed by the ocean, has been launched in the Gulf of Alaska, and is a new tool for researchers to examine how ocean circulation and ecosystems interact to determine how much CO_2 the North Pacific Ocean absorbs each year. *Credit: NOAA*

Ocean Modeling

Ocean currents have the ability to transfer large amounts of heat over great distances. Understanding the relationship between ocean currents and atmospheric and ocean temperatures is critical, especially because scientists have found evidence to suggest that past episodes of global warming have dramatically altered ocean circulation patterns.[6] Shifting currents could have a profound impact on global weather, including the location and timing of major weather patterns, such as seasonal monsoon rains. Ocean ecosystems and commercially important fisheries would also be severely affected, because so many organisms of the ocean have life cycles that depend on ocean circulation patterns. For these reasons, climate modelers must include as many details as possible about the sea in global climate models to improve climate predictions.

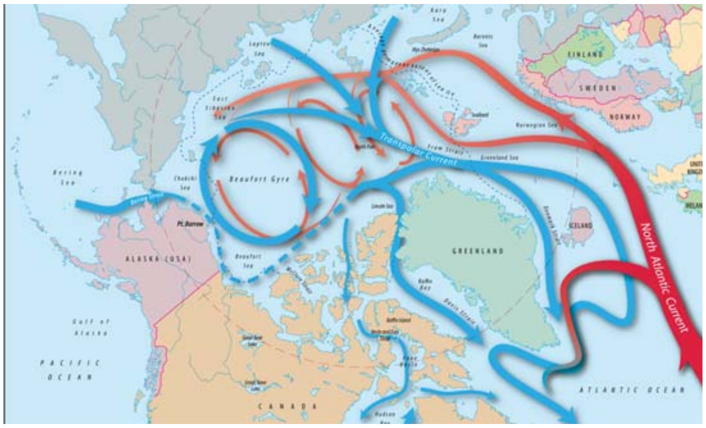
2 NCAR Research, Oceans and Our Atmosphere: www.ncar.ucar.edu/research/earth_system/oceans.php.

3 *The Academic Research Fleet: A Report to the Assistant Director for Geosciences*, 1999.

4 Solomon, S., et al., Technical Summary, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2007, p. 48.

5 NSF Highlight 16601: Ocean Acidification and Polar Ecosystems.

6 NSF Highlight 12174: Reversing Course: Changes in Ocean Currents During Global Warming.



Cold, relatively fresh water from the Pacific Ocean enters the Arctic Ocean through the Bering Strait. It is swept into the Beaufort Gyre and exits into the North Atlantic Ocean through three gateways (Fram, Davis, and Hudson Straits). Warmer, saltier waters from the Atlantic penetrate the Arctic Ocean beneath layers of colder water, which lie atop the warmer waters and act as a barrier, preventing them from melting sea ice. Once in the Arctic, this water is cooled as it travels cyclonically (counterclockwise) around the perimeter as a boundary current, finally exiting Fram Strait as a colder, fresher water mass. This warm-to-cold conversion is a crucial component of the global ocean's overturning circulation that helps maintain Earth's climate. *Credit: Illustration by Jack Cook, Woods Hole Oceanographic Institution*

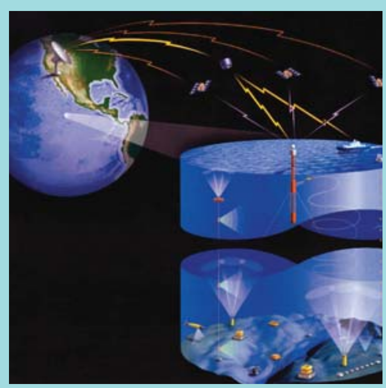
Air-Sea Exchange

NSF-sponsored investigators have deployed instrumentation to characterize the gas fluxes between the ocean and the atmosphere, with the aim of improving air-sea exchange simulations in global climate models. The instruments used for these measurements include shipboard sensors and buoys. Shipboard instruments enable researchers to study the geographic distribution of climatically relevant gas species, including marine-derived aerosol precursors.[7] Buoys allow researchers to characterize the air-sea exchange of gases such as CO_2 at a particular location over an extended period.[8] Both types of measurements provide critical information for increasing our understanding of ocean acidification and air-sea interactions under varying conditions.

The exchange of carbon dioxide and other gases at the air-sea interface is one of the most important interactions in the global climate system. Increased CO_2 concentrations in the world's oceans have led to increases in ocean acidity. *Credit: © University Corporation for Atmospheric Research*

Ocean Observatories Initiative

The Ocean Observatories Initiative (OOI) has the potential to revolutionize ocean science by providing the means to collect sustained, detailed, time-series data sets using state-of-the-art data maintenance and analysis tools. OOI was created in response to community demand for long-term and adaptive measurements in the world's oceans. OOI is envisioned as an international, integrated network of ocean-observing equipment that will enable researchers to study complex, interlinked physical, chemical, biological, and geological processes throughout the world's oceans. As planned, the observatory system would have three elements: a global component consisting of deep-sea buoys equipped with instrumentation; a regional electro-optical cabled network of interconnected sites around the seafloor; and new coastal observatory stations.[9] The scientific goals of OOI include gaining a greater understanding of carbon transfer to the oceans, the ecosystem consequences of ocean acidification, and the effects of climate change on coastal habitats.



The Ocean Observatories Initiative (OOI) promises to provide the ocean science research community with sustained, long-term, and adaptive measurements in the oceans via a fully operational research observatory system. *Credit: John Orcutt, Scripps Institute of Oceanography*

7 NSF Highlight 10407: Air-Sea Exchange Measurements by Eddy Correlation.

8 NSF press release 07-067: First Buoy to Monitor Ocean Acidification Launched: www.nsf.gov/news/news_summ.jsp?cntn_id=109619&org=GEO&from=news.

9 NSF-Supported Research Infrastructure: Enabling Discovery, Innovation, and Learning, 2008.

Academic Research Fleet

The researchers who study the biological, chemical, and physical processes of the ocean rely heavily on research vessels. The Academic Research Fleet consists of 23 vessels in the University-National Oceanographic Laboratory System. These vessels vary in size, endurance, and capabilities, and enable scientists supported by NSF and other Federal agencies to conduct marine research from coastal regions to the distant and deep seas. Funding for the Academic Research Fleet includes investments in ship operations, shipboard scientific support equipment, oceanographic instrumentation and technical services, and submersible support. NSF owns seven of the fleet's ships.[10]

Alaska Regional Research Vessel

The Alaska Regional Research Vessel (ARRV) will be the newest addition to NSF's complement of research ships. This technologically advanced, highly capable 242-foot ship is designed to operate in both seasonal ice and the harsh open waters surrounding Alaska. The ARRV will be able to accommodate 24 researchers on missions lasting up to 45 days, and the ship will be able to spend up to 300 days per year at sea. It will provide a crucial support platform to enhance scientific understanding of the polar regions and how they are affected by global climate change. The project is approaching the final design review, and ship construction is projected to get under way in early 2010. Scientific operations could begin in late 2013, following extensive sea trials and equipment testing.[11]

Ocean Climate Records

The depths of the ocean provide researchers with some of the best locations to seek evidence of Earth's climatic past. The anaerobic environment found in many deep seafloor locations prohibits marine organisms from disrupting the buildup of organic material, allowing millennia of ocean sediments to accumulate undisturbed. The ocean sediments contain the remains of living things, including foraminifera—microscopic single-celled organisms that build shells from minerals dissolved in seawater.

Foraminifera have played a pivotal role in revealing Earth's climatic past. Researchers can measure the ratio of oxygen isotopes contained in their shells to determine the temperature of the ocean at the time they were alive.[12] Seafloor core samples, including the remains of foraminifera and other sediments, provide scientists with a window into past climate conditions at a particular site. Arctic seafloor cores have revealed a subtropical past over 50 million years ago, when warmer global temperatures led to an abundance of living things near the North Pole.[13]

NSF's premier ocean core drilling project, the Integrated Ocean Drilling Project (IODP), is operated jointly with Japan's Ministry of Education, Culture, Sports, Science and Technology. IODP is an international marine research program that explores Earth's history and structure, as recorded in seafloor sediments and rocks. Japan's vessel, the *Chikyu* (Earth), was launched in January 2002, underwent outfitting and testing in 2003–2006, and began IODP operations in 2007.[14] (See the *JOIDES Resolution* sidebar for a description of the U.S. drilling vessel.)

The Integrated Ocean Drilling Program recovers rock and sediment samples, including drill cores like these, from the deep seafloor to the surface, allowing researchers to examine fossils and other clues about Earth's climatic past. *Credit: Integrated Ocean Drilling Program*

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10 NSF-Supported Research Infrastructure: Enabling Discovery, Innovation, and Learning, 2008.

11 NSF-Supported Research Infrastructure: Enabling Discovery, Innovation, and Learning, 2008.

12 NSF Highlight 12938: Evolution of the Eastern Tropical Pacific Through Plio-Pleistocene Glaciation.

13 NSF Highlight 10350: First Arctic Ocean Drilling Reveals Subtropical Past.

14 NSF-Supported Research Infrastructure: Enabling Discovery, Innovation, and Learning, 2008.

JOIDES Resolution

Illustration showing the ocean drillship *JOIDES Resolution* from the outside, following the completion of a total overhaul of the ship. *Credit: Illustration by Charles Floyd, Integrated Ocean Drilling Program*

The *JOIDES Resolution*, the U.S.-sponsored scientific ocean drilling vessel, has reached the completion of an extensive refitting operation. The ship is designed to support the recovery of sediment and crustal rock from the seafloor; the placement of observatories in drill holes to study the deep biosphere; and the long-term efforts of the Integrated Ocean Drilling Program to investigate solid Earth cycles, geodynamics, and processes relating to environmental change. During its initial 20 years of service, *JOIDES Resolution* expeditions produced significant contributions, including the discovery of "frozen" natural gas at shallow depths below the seafloor.[15] Core samples brought up during research expeditions have provided extensive information about Earth's past climate. The refitted vessel, which promises to improve the quality and rate of core samples brought up from the deep, includes more laboratory space, with instrumentation to analyze core samples while at sea.[16]

Antarctic Geological Drilling

A scientist points to an interesting feature in a slide of sediment core as part of the Antarctic Geological Drilling program. Sediment and rock core were analyzed to study climate change. *Credit: Peter West, National Science Foundation*

The ANDRILL (Antarctic Geological Drilling) program is a multinational collaboration comprising more than 200 scientists, students, and educators from five nations (Germany, Italy, New Zealand, the United Kingdom, and the United States). The researchers will drill "back in time" through Antarctic marine sediment to recover a history that will inform our understanding of how glacial and interglacial changes took place in the Antarctic. The researchers drill the continental margin seafloor below the vast ice shelves that extend off the coast of Antarctica. Researchers who are developing future scenarios of climate change benefit from guidance from the past. Sediment cores contain information that could reveal the potential frequency and locations of future changes.

The first two ANDRILL projects were successfully undertaken during the 2006–2007 and 2007–2008 Antarctic field seasons. Preliminary results indicate that the Ross Ice Shelf—an area the size of France that buttresses ice from both East and West Antarctica—is a dynamic feature that has collapsed during previous periods of global warming. The scientific community is currently analyzing the results of these projects, with many exciting discoveries expected. Several future projects are currently in development.[17]

U.S. Global Ocean Ecosystems Dynamics

The U.S. Global Ocean Ecosystems Dynamics (GLOBEC) program is a multidisciplinary research program designed by oceanographers, fishery scientists, and marine ecologists to examine how climate change affects marine ecosystems and fisheries. Through computer models, U.S. GLOBEC researchers are developing and applying large-scale observational programs using advanced technologies. GLOBEC uses a combination of modeling, broad-scale and time-series observations, and retrospective studies to gain insights into ecosystem dynamics on local, regional, and ocean basin scales to understand the fluctuations of marine animal populations.[18]

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15 NSF Highlight 13442: "Frozen" Natural Gas Discovered at Unexpectedly Shallow Depths Below Seafloor.

16 NSF-Supported Research Infrastructure: Enabling Discovery, Innovation, and Learning, 2008.

17 ANDRILL Web site: www.andrill.org.

18 GLOBEC Web site: www.globec.org.

Marine ecosystems rely on the tiniest microorganisms that form the foundation of the food chain; these are phytoplankton—microscopic drifting plants that absorb CO_2 and convert it into organic matter. The abundance of life on the higher stages of the marine food chain depends on the amount of phytoplankton, which in turn depends on the amount of dissolved nutrients in the seawater. Climate change affects circulation currents, which are responsible for the distribution of dissolved nutrients around the ocean. The GLOBEC program seeks to understand how climate change will alter the distribution and abundance of the entire marine ecosystem, including economically important fish species.

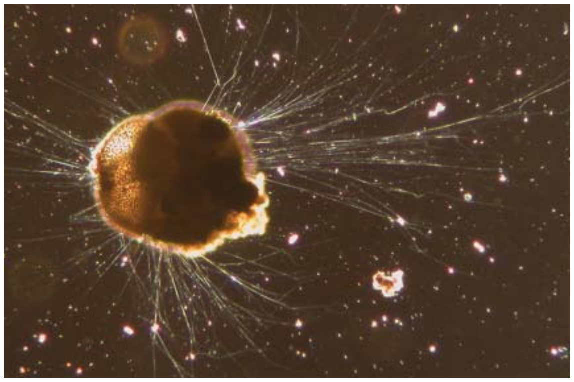
The Global Ocean Ecosystems Dynamics program was developed to study how climate change affects marine ecosystems and fisheries. *Credit: NOAA*

Conclusion

Earth's oceans hold some of its most varied and biologically rich ecosystems. In the decades since NSF-funded researchers began exploring the sea and its physical, chemical, and biological processes, they have uncovered evidence of change brought on by increasing temperatures and acidity. Their work is critical to the climate models and to improving our understanding of what will happen to the sea as a result of increasing carbon emissions and rising temperatures. The research highlights below describe some of the numerous NSF-funded projects that have contributed to our fundamental knowledge of the sea. The training these research projects provide to students ensures that we will continue to build our knowledge base about the world's oceans.

Sea Research Highlights

Reversing Course: Changes in Ocean Currents During Global Warming



Phase-contrast photomicrograph of a live *Ammonia tepida* benthic foraminiferan collected from San Francisco Bay. The remains of ancient foraminifera from ocean sediment cores provide scientists with detailed information about ocean circulation patterns in the past. *Credit: Scott Fay, University of California, Berkeley, 2005*

Ocean currents are considered the engine that drives Earth's climate because of their capacity to efficiently transport heat over great distances. At the same time, scientists have long suspected that global climate change may radically alter ocean circulation patterns. Now, researchers at the Scripps Institution of Oceanography have analyzed seafloor cores collected by the NSF Ocean Drilling Program (ODP) to provide the first direct evidence of sudden changes in ocean circulation patterns in response to global warming in Earth's distant past.

In a study published in the journal *Nature*, scientists Flavia Nunes and Richard Norris analyzed carbon trapped in the shells of microscopic, deep-sea fossil organisms called foraminifera to reconstruct past oceanic circulation patterns. Carbon is a good tracer for ocean currents because deepwater masses carry a different carbon signature at formation than they do as they age. Using foraminifera recovered in deep-sea cores from 14 sites in the Atlantic, Pacific, Indian, and Southern Oceans during the ODP (the predecessor to the current Integrated Ocean Drilling Program), the researchers examined the period bracketing a major global warming event that occurred 55 million years ago. The carbon analyses indicate that before and after this period, most deepwater formation occurred in the Southern Hemisphere. At the onset of global warming, though, deepwater formation switched from the Southern to the Northern Hemisphere over a period shorter than 5,000 years—a mere instant in geologic time. The hemispheric reversal in deepwater formation endured for approximately 40,000 years, but another 100,000 or more years was required for reversion to the ocean circulation patterns that predominated before global warming.

This study has revealed new details about an important, well-studied ancient global warming event and confirmed that global warming can lead to a rapid hemispheric switch in the locus of oceanic deepwater formation. In light of mounting evidence for contemporary global warming, the study suggests the possibility of future changes in ocean circulation. **Highlight ID: 12174 GEO/OCE**

Air-Sea Exchange Measurements by Eddy Correlation

Project co-investigator Byron Blomquist mounts inlets and a sonic anemometer on the jackstaff of the National Oceanic and Atmospheric Administration Research Vessel *Seward Johnson*. The atmospheric pressure ionization mass spectrometer laboratory container is in the foreground. *Credit: Barry Huebert, University of Hawaii*

This project is an innovative step toward a better understanding of air-sea interaction, in particular, gas fluxes between the ocean and atmosphere. The investigators have modified the newly developed atmospheric pressure ionization mass spectrometer (APIMS) for shipboard applications for measuring air-sea exchange of trace gas species important to global climate. Initial results for direct measurements of the sea-to-air flux of dimethyl sulfide (DMS), an important biogenic trace gas and natural secondary aerosol precursor, have been extremely successful. In a recent research article, the investigators report DMS exchange fluxes acquired over the open ocean on the NOAA research vessel *Seward Johnson* with unprecedented accuracy, and they plan to extend APIMS target species to include a number of other climatically relevant marine boundary-layer trace gas species. This tool will enable the measurement of DMS and other species with sufficient temporal resolution and accuracy to conduct critical process studies and improve parameterizations of air-sea exchange in global climate models. **Highlight ID: 10407 GEO/ATM**

Evolution of the Eastern Tropical Pacific Through Plio-Pleistocene Glaciation

A research team at Brown University recently produced the first continuous look at the evolution of sea surface conditions (past temperature and biological productivity) in the climatically sensitive Eastern Equatorial Pacific (EEP) over the past 5 million years. Their study monitored crucial aspects of the modern El Niño region as they evolved over the time when large ice sheets first began to wax and wane in the Northern Hemisphere.

The Brown team took advantage of new organic geochemical methods to determine past sea surface temperatures. They extracted alkenones—molecules synthesized by a class of marine algae—from a long deep-sea core recovered by the Ocean Drilling Program just south of the equator in the Eastern Pacific. Quantifying the ratio of two dominant alkenones allowed the investigators to determine past temperatures at the sea surface with high precision. The same sediment core also held clues to past ice ages, in the form of oxygen isotope ratios of bottom-dwelling foraminifera (single-celled organisms that make a carbonate shell). Because the bottom waters of the Pacific ultimately come from the high latitudes of the Northern and Southern Hemispheres, comparing the alkenone data (surface conditions) with the benthic isotope data allowed the Brown group to directly compare the response of an important tropical zone to the evolution of the ice ages at high latitudes. A principal finding of the Brown study is that the EEP has cooled rather steadily over the past 5 million years, at a rate of about 1 degree Celsius (1.8 degrees Fahrenheit) per million years. **Highlight ID: 12938 GEO/OCE**

First Arctic Ocean Drilling Reveals Subtropical Past

The Integrated Ocean Drilling Program completed the first-ever program of scientific drilling in the high Arctic with assistance from two icebreakers (background) that were used to protect the drillship (foreground). The results of the study are already revising our understanding of Arctic paleoclimate and the history of the Arctic Ocean basin. *Credit: Martin Jakobsson © ECORD/IODP*

The Integrated Ocean Drilling Program (IODP)—which is jointly sponsored by the National Science Foundation; the Japanese Ministry of Education, Culture, Sports, Science, and Technology; the European Consortium for Ocean Research Drilling; and the Chinese Ministry of Science and Technology—inaugurated a new era of drilling from specialized platforms with the 6-week Arctic Coring Expedition (ACEX), completed in summer 2004. Since the 1960s, international consortia have conducted scientific drilling in the world's oceans, but never before at such a high latitude, within a mere 250 kilometers of the North Pole. Constant vigilance by two icebreakers kept ice as thick as 4 meters from damaging the *Vidar Viking*, a specially modified vessel on which the British Geological Survey had installed its drilling equipment.

The cores recovered by ACEX comprise nearly 300 meters of sediments representing about 55 million years of Earth's history. Already, these samples have yielded results that revise our understanding of Arctic climate and the history of the Arctic Ocean. The oldest sediments recovered are from the Paleocene-Eocene Thermal Maximum, when Earth was significantly warmer than at present. Earlier models had suggested that the North Pole enjoyed a subtropical climate during this period; this has been confirmed by carbon isotopic analyses of ACEX sediment cores. The cores also challenge conventional wisdom about the opening of the Arctic Ocean basin, suggesting that the basin is older than predicted by plate tectonic reconstructions. A surprising discovery was more than 140 meters of laminated, organic-rich sediment that could indicate conditions conducive to oil formation in adjacent, deeper basins. Eventually, the ACEX cores are also expected to provide entirely new data on the timing of the establishment of icy conditions in the Arctic Ocean. (IODP's next drilling program from a specialized platform did not require icebreakers. In 2005, IODP drilled a Tahitian coral reef system to obtain a different kind of evidence for global climate change.) **Highlight ID: 10350 GEO/OCE**

Tracing Sea-Level and Environmental Change on Tahiti's Coral Reefs

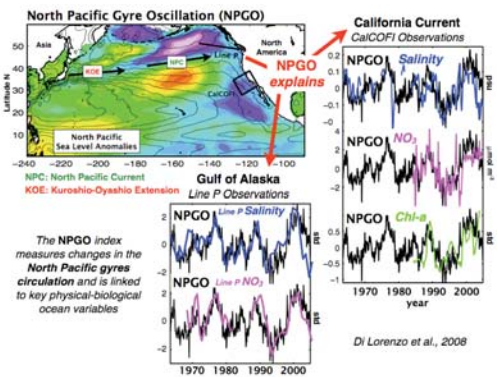
The mission-specific platform *DP Hunter*, used in Expedition 310.
Credit: IODP

The NSF-supported Integrated Ocean Drilling Program (IODP) Expedition 310 to the reef terraces around Tahiti, French Polynesia, was the second expedition to use a mission-specific platform. It was conducted by the European Consortium for Ocean Research Drilling Science Operator. Co-chief scientists for the expedition were Gilbert Camoin from France and Yasufumi Iryu from Japan. The objectives of Expedition 310 were to establish the course of postglacial sea-level rise at Tahiti, to define sea surface temperature (SST) variations for the region over the period 10,000–20,000 years ago, and to analyze the impact of sea-level changes on reef growth. The fluctuation of glacial ice sheets dramatically changes sea level and the salt content of the oceans, which in turn affect ocean currents and global climate. Because of the high resolution of annual growth rings in corals, coral reefs such as the one that surrounds Tahiti are excellent SST and sea-level indicators, and their accurate dating determines glaciation and deglaciation time periods. This unique record would not be possible without IODP drilling. These cores are now being analyzed to fulfill the Expedition 310 scientific objectives to establish the course of postglacial sea-level rise for the period 10,000–20,000 years ago, to define SST variations for the region over the same period, and to analyze the impact of sea-level changes on reef ecology. **Highlight ID: 13453 GEO/OCE**

"Frozen" Natural Gas Discovered at Unexpectedly Shallow Depths Below Seafloor

An international team of research scientists on NSF-funded Integrated Ocean Drilling Program (IODP) Expedition 311 set out to learn how gas hydrates are formed. The science party used the U.S. research drilling vessel *JOIDES Resolution* on a 43-day expedition in fall 2005. Gas hydrate, a largely frozen natural gas, is very important because it contains methane, a significant greenhouse gas. Gas hydrate is also a potentially important energy resource. Gas hydrate deposits are typically found below the seafloor in offshore locations where water depths exceed 500 meters (1,600 feet) and in Arctic permafrost regions. Contrary to established expectations of how gas hydrate deposits form, Expedition 311 scientists—led by Michael Riedel of McGill University, Montreal, and Timothy Collett of the United States Geological Survey—found unusually high concentrations of gas hydrate at relatively shallow depths: 50–120 meters (160–400 feet) below the seafloor. The lower pressure stability of gas hydrates means that they may be more accessible for mining, but they are also more easily released from sediments during seafloor landslides triggered by earthquakes, which are common in the geologically active area known as the (northern) Cascadia Margin near the coast of the Pacific Northwest, where the study took place. In addition, because methane is a greenhouse gas that contributes to global warming, and warming oceans may be a prime cause of "melting" of seafloor gas hydrates, there is a potential positive feedback: Warming oceans lead to more methane release, which leads to even more warming. **Highlight ID: 13442 GEO/OCE**

New Climate Mode of Variability, the North Pacific Gyre Oscillation, Links Ocean Climate and Ecosystem Change



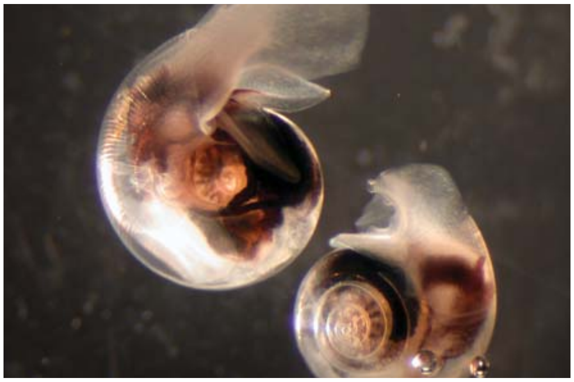
The North Pacific Gyre Oscillation (NPGO) is a pattern of climate variability that reflects changes in the strength of the North Pacific gyre's circulation (e.g., the North Pacific Current and the Kuroshio-Oyashio Extension Current). Changes in the NPGO are linked to previously unexplained climatic fluctuations of salinity and nutrients recorded in a long-term observational program in the California Current and the Gulf of Alaska. *Credit: Emanuele Di Lorenzo, Georgia Institute of Technology*

Decadal fluctuations in ocean salinity, nutrients, chlorophyll, a variety of zooplankton species, and fish stocks in the Northeast Pacific have been unexplained for many years. They are often poorly correlated with the most widely used indicator of large-scale climate variability in the region: the Pacific Decadal Oscillation (PDO). Researchers Emanuele Di Lorenzo of the Georgia Institute of Technology and Niklas Schneider of the University of Hawaii recently defined a new pattern of climate change—the North Pacific Gyre Oscillation (NPGO)—and showed that its variability is significantly correlated with the previously unexplained fluctuations of salinity, nutrients, and chlorophyll.

Fluctuations in the NPGO are driven by the same fundamental processes that control salinity and nutrient concentrations. In the California Current System, the NPGO particularly reflects changes in the winds that cause coastal upwelling, the process by which subsurface cold water that is rich in nutrients is brought up to the surface. These results strongly support the use of the NPGO as the primary indicator of upwelling strength and nutrient fluxes, and, therefore, the potential for ecosystem change in the California Current System region. Changes in nutrient fluxes drive fluctuations in modeled chlorophyll concentration—an indicator of phytoplankton concentration—that are highly correlated to observed chlorophyll. The model simulations support the hypothesis that variations in phytoplankton biomass in the California Current System region are primarily driven by changes in wind-driven upwelling correlated with the NPGO. The NPGO thus provides a strong indicator of changes in the mechanisms driving oceanic ecosystem dynamics.

This "bottom-up" forcing is consistent with previous fish catch data and satellite-derived chlorophyll concentration, and underscores the need to better understand the influences of physically forced nutrient fluxes on higher food-chain levels in the ocean. The researchers have also shown that the NPGO pattern extends beyond the North Pacific and is part of a global mode of climate variability that is evident in global sea-level trends and sea surface temperature. The amplification of the NPGO variability found in observations and in model simulations of global warming scenarios implies that the NPGO may play an increasingly important role in forcing global-scale decadal changes in marine ecosystems. **Highlight ID: 16644 GEO/OCE**

Ocean Acidification and Polar Ecosystems



The Antarctic pteropod *Limacina helicina antarctica*, seen here under the microscope, is about the size of a pepper grain and is a notable component of the zooplankton around McMurdo Station, Antarctica. Increased atmospheric carbon dioxide may inhibit this animal's ability to grow its calcium carbonate shell. *Credit: Gretchen Hoffman, University of California, Santa Barbara*

Ocean acidification arises as a result of the ocean's absorption of carbon dioxide (CO_2), followed by a series of naturally occurring equilibrium reactions involving carbonate, bicarbonate, and the hydrogen ion, which together constitute the carbonate cycle. One outcome of these equilibrium reactions is an increase in hydrogen ion concentration (i.e., lower pH) and a decrease in the carbonate ion available for the formation of calcium carbonate. Calcium carbonate is an important skeletal component for many marine organisms, including coral and shell-bearing invertebrates. Undersaturation of oceanic waters with respect to carbonate could promote shell dissolution or inhibit shell formation.

The implications for marine organisms, ecosystems, and biogeochemistry of ocean acidification are potentially profound. If shell-bearing species cannot form skeletons or if organisms with shells encounter undersaturated waters, marine biodiversity, food web structure, and biogeochemical function are potentially affected. Non-shell-bearing organisms also may be at risk, because pH influences physiological processes and metabolic reactions in other organisms, as well as sorption-desorption reactions of metals and toxins.

Polar ecosystems are particularly vulnerable to ocean acidification because cold water holds more $CO_{2;}$ therefore, surface waters in the polar oceans are closer to the tipping point of undersaturation. Models predict that the Southern Ocean could become undersaturated with respect to aragonite, a fragile biogenic form of calcium carbonate, by the year 2100. Polar ecosystems include critical members (e.g., pteropods, coccoliths) that depend on calcium carbonate formation for skeletal or protective components. Food web structure and carbon burial may be substantially altered.

Researchers Vicky Fabry of California State University, San Marcos, Brad Seibel of the University of Rhode Island, and Gretchen Hofmann of the University of California-Santa Barbara are taking a multipronged approach to determining the response of Southern Ocean pteropods, an important group of zooplankton, to ocean acidification. Fabry and Seibel are quantifying the impact of elevated CO_2 and carbonate-undersaturated seawater on rates of shell formation and sublethal effects on organism energetics. Hofmann is investigating the response of pteropods at the genetic level to calcification stress. Her research on sea urchin larvae shows that shell-forming genes have highly elevated activity and larval skeletons are less developed when the larvae are subjected to undersaturated seawater; this is consistent with Intergovernmental Panel on Climate Change scenarios of ocean conditions in the future. Hofmann is now using gene microarrays to examine the genomic response of Antarctic pteropods to elevated atmospheric CO_2 and undersarurated seawater, in concert with Fabry and Seibel's calcification and energetic studies. **Highlight ID: 16601 OPP/ANT**

Marine Radiocarbon Evidence for the Mechanism of Deglacial Atmospheric Carbon Dioxide Rise

Species *Angulogerina earlandi*, a benthic (lives on the bottom of the ocean) Antarctic foraminifera. This organism produces a shell made of calcium carbonate. *Credit: Scott McCallum and Scott Ishman*

Before humans influenced the climate system, natural processes controlled atmospheric greenhouse gas concentrations. One of the great mysteries surrounding Earth's emergence from the last ice age, which occurred between 19,000 and 11,000 years ago, is the rapid increase in atmospheric carbon dioxide (CO_2) that occurred as the glacial ice sheets melted. Scientists have known that during this time, the carbon-14 (^{14}C, an unstable isotope of carbon) content of the atmosphere fell by approximately 35 percent. The current hypothesis for this radiocarbon conundrum—the rapid rise in the level of atmospheric CO_2 as the ^{14}C content of the atmosphere fell—is that a large reservoir of deep ocean water with accumulated CO_2 suddenly reached the surface and released CO_2. The stored CO_2 molecules would have been isolated from the atmosphere for thousands of years (which would decrease its ^{14}C level), thereby giving CO_2 in the postglacial atmosphere the appearance of being older (because it contained less ^{14}C).

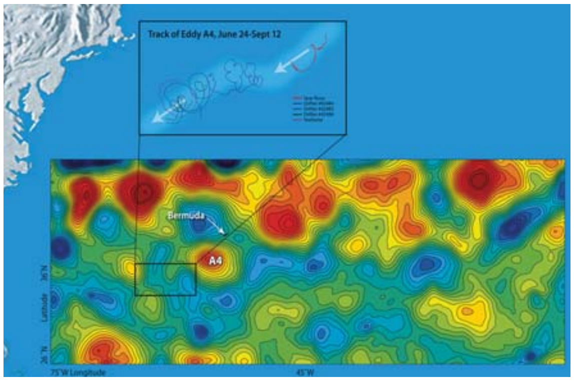
The search for this "old" water has finally revealed its first clue. By analyzing the ^{14}C content of fossilized, bottom-dwelling foraminifera (single-celled amoeba-like organisms with shells) from a core collected from a depth of 700 meters off the coast of Baja California, a team of NSF-funded scientists led by Thomas Marchitto of the University of Colorado has located the missing water mass: ^{14}C data from these samples show two periods during the deglaciation when these intermediate water-depth sediments were in contact with old ^{14}C-depleted waters. The researchers propose that during the deglaciation, a deep reservoir of old water spread northward from the Southern Ocean via the Antarctic Intermediate Water Current. When this old, CO_2-rich, ^{14}C-depleted water surfaced along the Baja coast and elsewhere, the excess dissolved CO_2 in the water left the ocean. This had the effect of reducing the atmosphere's radiocarbon content and contributed to the rapid CO_2 rise in the atmosphere, as documented in high-latitude ice cores. These findings have provided the first direct evidence for a deep ocean deglacial CO_2 source and a testable hypothesis to resolve this fundamental mystery. **Highlight ID: 16475 GEO/OCE**

Tracking the Ocean's Motion, Temperature, and More

NSF-funded researchers are creating sophisticated computer models to simulate the role the world's oceans play in global climate. *Credit: © 2009 JupiterImages Corporation*

The vast size and heat capacity of the world's oceans give them a pivotal role in Earth's climate. Other important ocean issues include biodiversity, fisheries dynamics, shipping, and international policy. But the sheer magnitude and remoteness of the oceans, which cover 70 percent of Earth's surface, also make them difficult and expensive to observe. With the help of researchers at the NSF-funded San Diego Supercomputer Center (SDSC), climate scientist Carl Wunsch and other scientists in the Estimating the Circulation and Climate of the Ocean Consortium are working to better estimate the physical conditions in the world's oceans—velocity, temperature, salinity, and other factors. By harnessing the power of SDSC's supercomputers to create a vast simulation or "virtual ocean," the scientists can tease out accurate estimates of the ocean's state by filling in the gaps between the relatively tiny number of ocean measurements made. To help climate scientists and others, the team is producing the most accurate information ever available about conditions in the ocean. More information on this research can be found at www.ecco-group.org. **Highlight ID: 14385 OD/OCI**

Interactions Between the Wind and Oceanic Eddies Stimulate Higher Biological Productivity in Subtropical Ocean Surface Waters

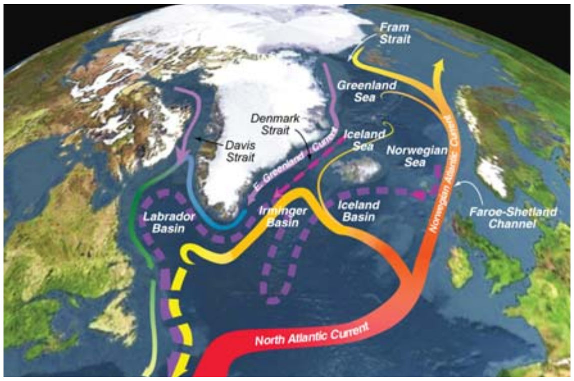


Data from satellite altimeters (lower inset), which measure sea surface heights, show depressions (blue) and bumps (red) that mark cold- and warm-water eddies in the ocean on June 17, 2005. Researchers tracked the southwestward motion of eddy A4 (light-blue in the upper inset) by ship from June 24 to September 12. They released several drifters and a buoy (colored tracks) to capture the swirling motion of the eddy's currents. *Credit: This figure was drafted by Jim Canavan and provided as a courtesy by Dennis McGillicuddy, Woods Hole Oceanographic Institution, and the Colorado Center for Astrodynamics Research.*

Oceanographers participating in the NSF-funded Eddies Dynamics, Mixing, Export, and Species composition (EDDIES) study have demonstrated that episodic, eddy-driven upwelling—in which ocean surface waters are replaced by water that comes up from below—may supply a significant fraction of the nutrients required to sustain primary productivity in the subtropical ocean. The importance of ocean eddies (circular, rotating bodies of ocean water with warm or cold water cores) in stimulating ocean productivity through the enhanced upwelling of cold, nutrient-rich water to the surface had been speculated for over a decade. Large areas of the ocean, such as the central subtropical North Atlantic, are characterized by low productivity, largely because phytoplankton growth is limited by the delivery of plant nutrients to the sunlit surface zone. Nevertheless, productivity in these regions is higher than expected based on current knowledge of ocean mixing processes. In 2004 and 2005, EDDIES researchers sampled 10 different ocean eddies in the Northern Atlantic Ocean. Two different types—a "cyclone" eddy (counterclockwise rotating with density surfaces pushed up in the center in a dome shape) and a "mode-water" eddy (clockwise rotating with a thick lens of constant density water below the surface)—were sampled repeatedly. The different types have distinct surface signatures that allow researchers to use remote sensing techniques to locate them, then tag and track them by releasing surface drifters in their core. This sophisticated approach allowed the researchers to sample the eddies and their evolution in great detail over 2 months, tracking them using two research vessels and employing high-tech instrumentation, such as a video plankton recorder, acoustic doppler current profiler, conductivity, temperature, depth recorders, and a tracer that directly measured the horizontal and vertical dispersion of water properties such as temperature, salinity, and plankton concentration.

The main result of this study is that the interactions of cyclone and mode-water eddies with the wind result in very different biological responses. The eddy-wind interactions enhance the vertical supply of nutrients in mode-water eddies by moving surface water away from the center of the eddy. The result is sustained primary biological production at the surface and the creation of subsurface maxima in phytoplankton and zooplankton communities. In contrast, the biological production in cyclones is more ephemeral because of a reverse effect of the wind interacting with cyclones. These results explain how higher than expected production can be achieved in mid-ocean regions and points to the need to include explicit representations of eddy-wind interactions and response in future ocean and climate models. **Highlight ID: 16578 GEO/OCE**

How Much Excess Freshwater Was Added to the North Atlantic in Recent Decades?



Map of the Nordic Seas with ocean circulation. Surface currents are shown as solid pathways; deep currents are dashed. Color depicts temperature of water. *Credit: Ruth Curry, Woods Hole Oceanographic Institution*

Large regions of the North Atlantic Ocean have become fresher since the late 1960s as melting glaciers and increased precipitation, both associated with greenhouse warming, have enhanced continental runoff into the Arctic and sub-Arctic seas. Over the same time, salinity records show that large pulses of extra sea ice and freshwater from the Arctic have flowed into the North Atlantic. However, until now, the actual amounts and rates of freshwater accumulated have not been explicitly known. According to climate models, excessive amounts of freshwater could alter the ocean density that drives a portion of the circulation system, diminish the amount of heat that is transported northward, and significantly cool areas of the Northern Hemisphere.

Ruth Curry at Woods Hole Oceanographic Institution and Cecilie Mauritzen at the Norwegian Meteorological Institution have analyzed data collected in the North Atlantic over the past 55 years to estimate how much freshwater had to have been added to the North Atlantic to account for the observed changes in salinity. In an average year, about 5,000 cubic kilometers of freshwater flows from the Arctic into the North Atlantic. This is approximately 10 times more water than the Mississippi River outflow. However, between 1965 and 1995, an extra 19,000 cubic kilometers of freshwater has diluted the northern seas. **Highlight ID: 11593 GEO/OCE**

Science and Technology Center for Coastal Margin Observation and Prediction

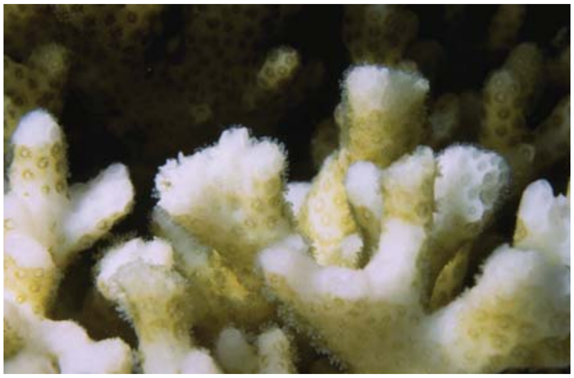
Coastal margins are among the most densely populated and developed regions in the United States. They sustain highly productive ecosystems and resources, are sensitive to many scales of variability, and play a key role in global elemental cycles. Natural events and human activities place stresses on coastal margins, making the development of sustainable coastal resources and ecosystems difficult and contentious, with many policy decisions historically based on insufficient scientific input. Science as usual will not suffice; sustained advances at the interfaces of disciplines, technologies, and scales are required to an extent unprecedented even in interdisciplinary oceanography.

In 2006, NSF awarded a grant to support a new Science and Technology Center for Coastal Margin Observation and Prediction (CMOP). The mission of the CMOP is to study coastal margins using observation and prediction technologies to facilitate long-term integrated descriptions and analyses of coastal margin physics, chemistry, and biology. CMOP will enable researchers to focus on novel technological and scientific opportunities to answer major questions about the impact of climate on coastal margins, the role of coastal margins on global elemental cycles, and the seaward extent of human impacts. This work, focused on the Columbia River, will lead to transformative understanding of critical yet vulnerable river-to-ocean ecosystems.

The CMOP partnership is anchored in complementary expertise from Oregon Health and Science University, Oregon State University, and the Applied Physics Laboratory at the University of Washington. All three institutions have strong research, education, and outreach assets in the Pacific Northwest. Essential elements of the Science and Technology Center are educational partners and industry partners initially focused on advanced computing and visualization technology, oceanographic instrumentation, and molecular sensors.

Integral to CMOP is a river-to-ocean testbed observatory for the Pacific Northwest, consisting of modeling systems, observation networks, and information systems—all aimed at fundamental advancements in science and the delivery of more reliable information to scientists, educators, resource managers, and interested citizens. **Highlight ID: 14056 GEO/OCE**

Coral Reef Bleaching: A Novel Strategy for Survival



The polyps in this coral colony are partially bleached. Polyps on the top are completely clear, while those on the sides of the branched colony still have some coloration from their zooxanthellae. *Credit: Mark Eakin, NOAA Coral Reef Watch*

Of the many documented effects of global climate change, the bleaching of corals—a stress response caused by elevated seawater temperature in which corals lose their nutrient-providing symbiotic algae (called zooxanthellae)—continues to attract the interest of coral reef biologists around the world. Recent research conducted by Andrea Grottoli from Ohio State University at the Hawaii Institute for Marine Biology has revealed that when certain corals bleach, they can continue to survive by consuming zooplankton from the surrounding seawater.

While corals have long been known to consume zooplankton, some species of coral appear to be able to survive bleaching by increasing their rates of feeding to compensate for the loss of food normally supplied by the zooxanthellae when these cells reside safely in their coral host. Grottoli and her group made this discovery by conducting feeding and physiological studies on three species of coral found on reefs in Hawaii. An often-noted effect of coral bleaching is that corals with a mounding shape or morphology are more likely to survive a bleaching event than those with a branching morphology. The study found that one of these species, the branching coral *Montipora capitata*, exhibited the greatest increase in feeding on zooplankton after bleaching and recovered faster as well, but another branching species, *Porites compressa*, did not.

The implications of these results are that predicting coral survival or recovery on the basis of morphology does have exceptions, and many species of coral may be able to survive the repeated effects of thermal stress and bleaching by increasing their feeding rates. Increased feeding in the face of continuing environmental stress depends on the availability of zooplankton in the water, which may also be affected by the very same thermal stress events that cause corals to bleach. **Highlight ID: 13490 GEO/OCE**

Saltier Tropical Oceans and Fresher Ocean Waters Near the Poles: More Signs of Global Climate Change

Tropical ocean waters have become dramatically saltier over the past 40 years, while oceans closer to Earth's poles have become fresher. These large-scale, relatively rapid oceanic changes suggest that recent climate changes, including global warming, may be altering the fundamental planetary system that regulates evaporation and precipitation and cycles freshwater around the globe. The study, led by Ruth Curry of the Woods Hole Oceanographic Institution (WHOI), provides direct evidence that the global water cycle is intensifying. This result is consistent with global warming hypotheses that suggest ocean evaporation will increase as Earth's temperature does. By comparing recent and historical salinity observations, the investigators observed that surface waters in tropical and subtropical Atlantic Ocean regions have become markedly saltier. Simultaneously, much of the water column in the high latitudes of the North and South Atlantic became fresher. This trend appears to have accelerated in the years since 1990, when 10 of the warmest years occurred since records began in 1861. The scientists estimated that net evaporation rates over the tropical Atlantic have increased by 5 percent to 10 percent over the past four decades. These findings are particularly significant as pressure on freshwater resources has become critical in many areas around the world. An acceleration of Earth's global water cycle can potentially affect global precipitation patterns that govern the distribution, severity, and frequency of droughts, floods, and storms. It would also exacerbate global warming by rapidly adding more water vapor—itself a potent, heat-trapping greenhouse gas—to the atmosphere. And it could continue to freshen North Atlantic Ocean waters to a point that could disrupt ocean circulation and trigger further climate changes. **Highlight ID: 8053/ Press Release** 03-145 GEO/OCE