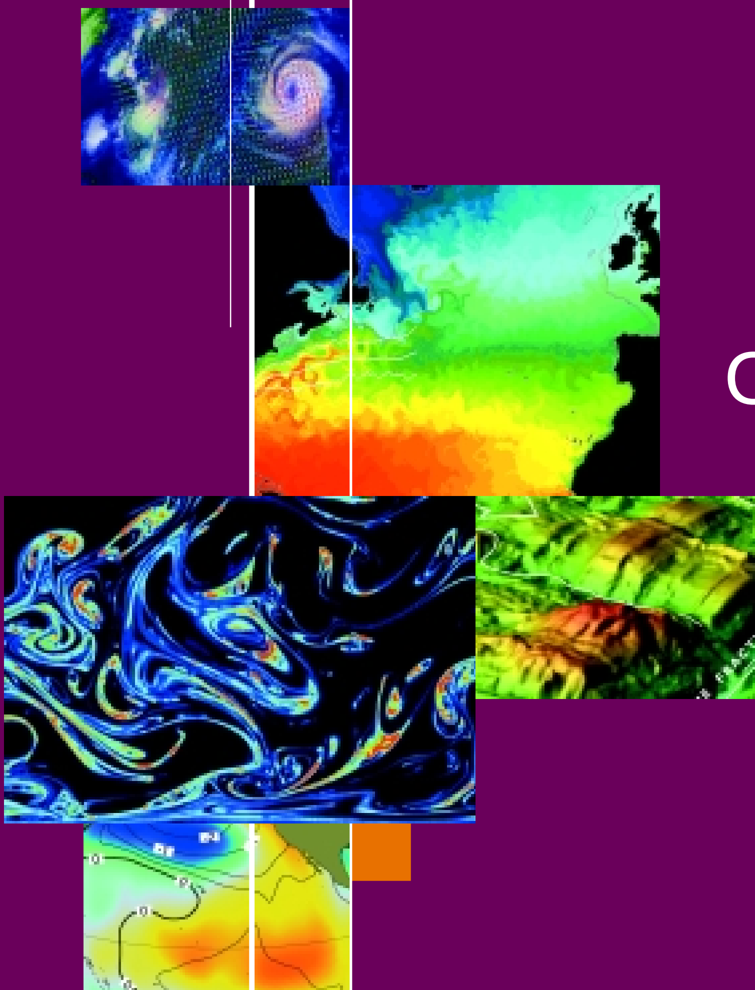
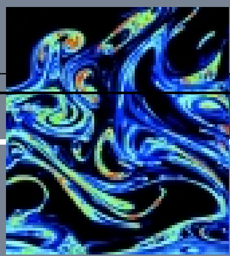


OCEAN SCIENCES

AT THE NEW MILLENNIUM

SUMMARY



About the Ocean Sciences Decadal Committee...

In 1998, the National Science Foundation's Division of Ocean Sciences invited several members of the academic research community to report on the "most important and promising opportunities for discovery and new understanding" in ocean sciences in the coming decade. This Decadal Committee sought the widest possible input from the community, and that input is incorporated into their final report, *Ocean Sciences at the New Millennium*. This booklet summarizes the Decadal Committee's findings.

Committee Membership

Robert Beardsley	Woods Hole Oceanographic Institution
Rainer Bleck	Los Alamos National Laboratory
Peter Brewer*	Monterey Bay Aquarium Research Institute
Kenneth Bruland	University of California, Santa Cruz
Russ Davis	University of California, San Diego
Jody Deming	University of Washington
Robert Detrick	Woods Hole Oceanographic Institution
Stanley Hart	Woods Hole Oceanographic Institution
Mark Hay	Georgia Institute of Technology
Peter Jumars	University of Maine
Ellen Kappel**	Geosciences Professional Services, Inc.
David Karl	University of Hawaii
Cindy Lee	State University of New York, Stony Brook
Susan Lozier	Duke University
Donal Manahan	University of Southern California
Larry Mayer	University of Maine
Marcia McNutt	Monterey Bay Aquarium Research Institute
Frank Millero	University of Miami
Ted Moore*	University of Michigan
Mark Ohman	University of California, San Diego
Peter Rhines	University of Washington
Eli Silver	University of California, Santa Cruz
Sharon Smith	University of Miami
Karl Turekian	Yale University
Francisco Werner	University of North Carolina

* Decadal Committee Co-Chair
** Ex Officio Member

OCEAN SCIENCES

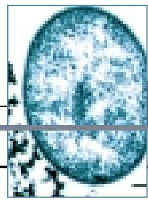
AT THE NEW MILLENNIUM

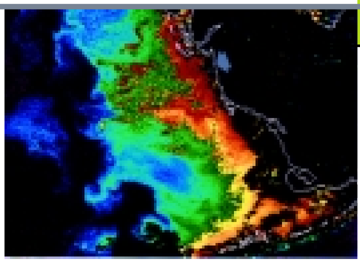
The oceans play a pivotal role in regulating Earth's climate, provide the largest and most unexplored habitat for life, and serve as routes for commerce and sites for recreation. Food and energy resources that modern society requires are found in and beneath the oceans. Processes occurring deep below the seafloor along many continental margins are the cause of some of Earth's greatest earthquakes and most explosive volcanoes.

The oceans contain organisms and hold information that can be used to improve public health. Recently discovered subseafloor microorganisms that live under extreme environmental conditions are now broadly considered a potential source of biomaterials and are the basis of ideas for new biotechnical applications. Monitoring the ocean's temperature fluctuations may help predict outbreaks of infectious diseases in tropical coastal nations. The unintentional transport by ships of organisms to new regions can cause troublesome ecosystem shifts.

In the decade ahead, ocean scientists will be challenged by the urgent need to better understand humankind's impact on the coastal ocean, on chemical and biological systems, and on global climate. Assessing the impact of rapid changes in biological populations will permit wiser protection and management of marine ecosystems. Studies providing information about links among the different parts of the Earth system will produce better predictive models of climate and ecosystem change. Exploring the largely unknown oceanic realm beneath the seafloor will permit better understanding of the impact of fluid flow on earthquake generation and mineral accumulation at and below the seafloor.

Meeting these future scientific challenges requires a robust research fleet; incorporating new platforms for ocean observation and sampling; expanding the effort to acquire long-term records of the oceans and the earth below; developing miniaturized sensors to measure physical, chemical, geological and biological structure of the ocean in four dimensions; and improving the ability to assimilate data and update integrated forecast models. New technologies and novel experiments provide opportunities for great progress in ocean sciences at the new millennium.





2 TWO

SCIENCE THEMES

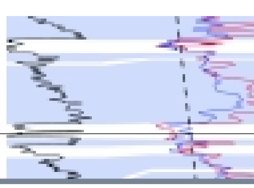
THE OCEAN'S ROLE IN GLOBAL CLIMATE

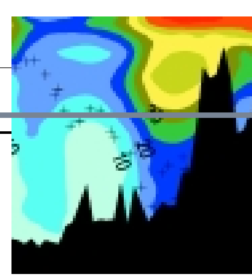
The ocean plays a critical role in establishing global climate and is inextricably linked to the atmosphere in creating the natural fluctuations of our climate system. Absorbing and distributing vast quantities of heat, and dominating the hydrologic cycle, the ocean rivals the atmosphere in regulating global temperatures. Through its enormous heat capacity, the ocean stores heat on a much longer time scale than the atmosphere. And, by virtue of its alkalinity, or buffering capacity, the ocean absorbs and stores vast quantities of carbon dioxide. As a reservoir and transfer agent for heat, water and carbon dioxide, the ocean stabilizes our planet's climate.

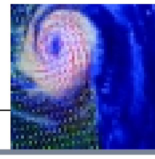
The ocean's capacity to absorb and store heat gained from the atmosphere delayed our recognition of anthropogenic climate change. To understand humankind's impact on climate, and possibly modify our present course, we must be able to distinguish between Earth's natural climate variability and that part of the climate system fluctuating as a result of, for example, the input of anthropogenic greenhouse gases. Ocean observations, theory and modeling are all essential for meeting this challenge.

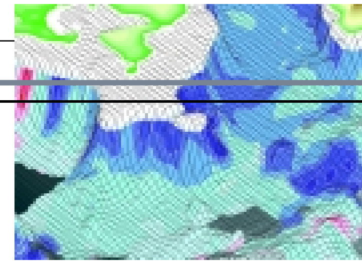
Specific challenges to address in the next decade include:

- detecting and understanding climatic fluctuations in heat budgets, in hydrologic cycles and in greenhouse gases with sufficient accuracy to better predict climate change and to assess the effects of human intervention;
- understanding what types of ocean conditions caused abrupt (within a human life span) climate changes in the geological past, and what the consequences were to the ocean's ecosystems and to the atmosphere;
- developing and testing predictive models of the great natural fluctuations in climate, such as the El Niño and North Atlantic Oscillation events;
- determining the ocean's deep- and intermediate-water pathways for distributing heat and carbon dioxide and how the pathways influence the lag between atmospheric input and response.









LONG-TERM OCEAN OBSERVATIONS AND PREDICTION

The 1.2 billion cubic kilometers of ocean on Earth comprises resources, ecosystems and a massive part of the dynamical climate system. The ocean's surface and deep circulation affects marine resource management, ship movement, climate and ecosystem stability. Accurately forecasting circulation patterns is essential.

To make the next leap in model reliability and ocean prediction, the ocean's baseline physical, biological, chemical and geological properties must be gathered in greater detail, and over long periods of time. Deploying new and innovative technologies now available permits vastly more efficient exploration of the ocean. "Images" of this three-dimensional space, coupled with global satellite sensing, augment classical expeditions on research vessels. Theory and computer models incorporate the data from these observations, enhancing understanding and prediction capabilities. These strategies will allow scientists to make significant advances in addressing urgent ocean prediction problems such as:

- understanding the links between ocean circulation changes and shifts in climate on time scales of years to several decades;
- modeling the ocean's global, density-driven circulation with sufficient accuracy to allow improved climate prediction;
- assessing the fundamental links between physical and biological processes that lead to major ecosystem shifts;
- evaluating the large-scale increases in fresh water input to the ocean, and the resulting changes in density-driven ocean circulation, that are predicted to occur as result of climate change.

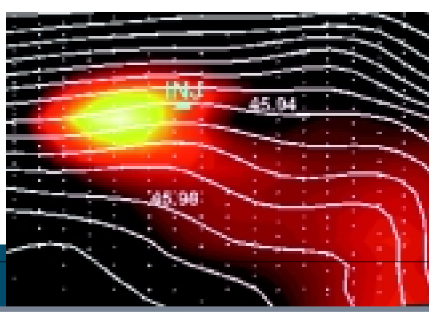
4 FOUR

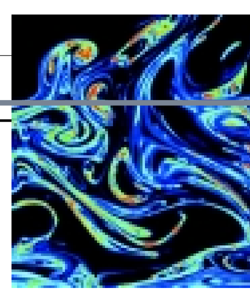
OCEAN TURBULENCE

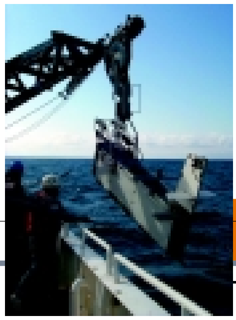
Turbulence plays a critical role in the transfer of mass, momentum and heat throughout the oceans. It affects processes as diverse as zooplankton detection of prey and avoidance of predators, transfer of carbon dioxide across the air-sea interface, and mixing of the ocean's heat and nutrients. A better understanding of ocean turbulence and its role in ocean mixing, and how ocean mixing can be accurately described mathematically, is essential for developing new ocean circulation models. These models will permit studies ranging from local ecosystem dynamics to the ocean-atmosphere climate system. Significantly extending innovative chemical tracer studies, expanding capabilities for numerical simulation, and deploying new sensors for observing ocean turbulence will lead to important breakthroughs in this field.

Key challenges in the coming decade include:

- determining the triggers for different scales of turbulent mixing across density boundaries in the ocean, and how turbulent mixing moves heat, dissolved material and biota;
- understanding the extent to which turbulence, over a broad range of scales, affects rates and consequences of biological interactions;
- assessing how ocean eddies with dimensions of kilometers to hundreds of kilometers, and which move large amounts of salt, heat and planktonic communities across vast areas of the ocean, affect the larger-scale, more slowly moving general ocean circulation;
- evaluating the relative roles of wind and evaporation in heat, gas and energy exchange in the upper-ocean "mixed" layer above the thermocline.





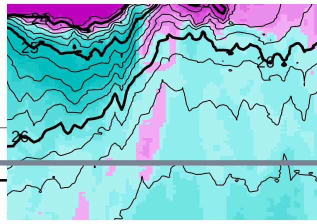


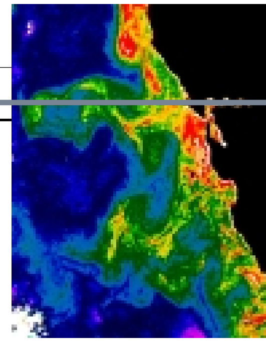
NON-EQUILIBRIUM
ECOSYSTEM DYNAMICS

Climate properties, marine communities and entire ecosystems all can change rapidly with little warning. Sometimes changes are cyclical. In other instances alterations to the biodiversity, structure and functioning of marine ecosystems persist for long periods without reversion to the previous state. A better understanding of these changes and the mechanisms driving them is necessary to predict the future state of marine ecosystems, wisely protect and manage these ecosystems, and sustain the many critical services that they provide.

The realization that marine ecosystems are commonly in disequilibrium and can change dramatically over short periods presents opportunities for ocean scientists from different disciplines to collaborate on a spectrum of ecosystem studies, including:

- determining how physical changes in the environment directly and indirectly affect the structure and function of marine communities;
- understanding how internal processes, such as altered population densities of a top predator, affect the composition and function of the ocean's biota;
- detecting the triggers of harmful algal blooms, and developing measures to control them;
- identifying which characteristics of an "invader" make a particular species successful, and which properties make an invaded ecosystem more or less susceptible to invasion;
- determining the effects of pathogens and parasites on populations, communities and ecosystems, and how biota naturally defend against them.





THE COMPLEX COASTAL OCEAN

The ocean margin occupies only about 10% of the global ocean area and a much smaller fraction of its volume, but hosts the sea's most economically significant activities, including fish harvest, sand and gravel mining, waste disposal, petroleum extraction and recreation. In the United States and other nations, most humans live in the terrestrial part of the coastal zone. Accumulating human impact on the coastal zone has created an urgent need for better understanding of the processes that influence and control this environment. Important issues include the carbon cycle, coastal food webs and sustainable fisheries, harmful algal blooms, coastal erosion and flooding, and long-term effects of climate change and sea-level rise.

There is growing consensus that many of the features of coastal ecosystems arise from the rapid, energetic and episodic inputs, outputs and transport processes through and within the coastal zone. Using appropriate instrumentation to gather data over longer time periods is essential for capturing important events in this zone. Some of the major challenges in coastal research in the next decade include:

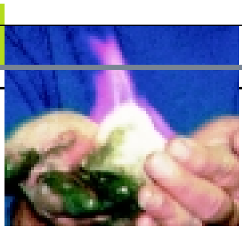
- determining the ways in which increased material fluxes from the land, particularly of nutrients, pollutants and sediments, affect the chemistry of the oceans and ecosystem processes;
- understanding how the physics of the coastal environment drive other oceanic processes;
- comparing how margins with different physical characteristics move sediments and nutrients from the coastal zone to the open ocean, and import and process materials delivered from the open ocean;
- assessing how local stocks and diversities of organisms are maintained by physical and genetic connections to adjacent and distant coastal stocks.

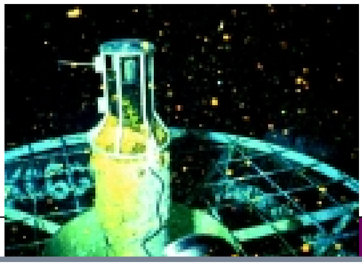
THE OCEAN BELOW THE SEAFLOOR

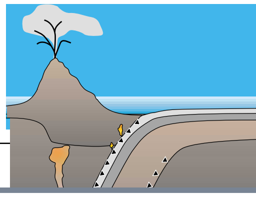
Water flowing through cracks and pores in oceanic crust and sediment contributes to the formation of gas hydrates and mineral resources, lubricates earthquake-generating faults, influences the chemical composition of the ocean, and supports remarkable microbial communities that have already found important applications within the biotechnology industry. The region beneath the seafloor is an exciting new research frontier in the ocean sciences. It presents enormous opportunities for fundamental new insights into linked geological, physical, chemical and biological processes in the deep sea.

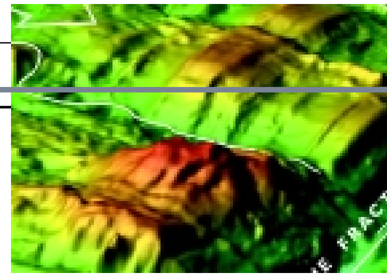
Studying subseafloor fluid flow requires making the right combinations of measurements, over long time periods and under *in situ* conditions, and reconciling the different temporal and spatial scales of fluid flow. Specific challenges in the next decade include:

- determining the physical boundaries of subseafloor fluid flow, and the forces responsible for driving it;
- understanding the influence of fluid flow on earthquake generation, hydrocarbon accumulation and mineral deposition at and below the seafloor;
- measuring the fluxes of mass, heat and chemicals to and from the subseafloor ocean to determine their contribution to global cycles of carbon, oxygen, metals and other elements;
- obtaining sediment and fluid samples with wide geographic distribution and at many depths to assess how and to what extent the subseafloor biosphere takes part in global biogeochemical cycling;
- determining the impact of fluid fluxes and subseafloor biological communities on mineral, chemical and biological resources.









DYNAMICS OF OCEANIC
LITHOSPHERE AND MARGINS

Oceanic crust constitutes over 60% of Earth's surface, and its creation at submarine spreading centers accounts for over 90% of global volcanic activity. The recycling of oceanic crust and upper mantle at subduction zones, such as Japan, the Cascades and the Aleutians, accounts for most of the globe's devastating explosive volcanic activity and its most destructive earthquakes. Increasing evidence suggests that mantle dynamics and lithosphere recycling play a role in environmental change and natural resource accumulation.

Recent advances in mapping the seafloor and determining its evolution on geologic time scales have opened the door to acquiring significant understanding of the processes that govern Earth's behavior. Fundamental challenges to tackle in the next decade include:

- determining which processes control the frequency of large subduction earthquakes, and which properties of an active fault system should be measured to better assess seismic and tsunami risk;
- quantifying how volcanic activity focuses along discrete eruptive centers (such as island arcs and mid-ocean ridges), concentrating mass and energy transfer from the mantle to the crust, and greatly magnifying the thermal and chemical gradients driving hydrothermal and biological processes;
- observing short-lived volcanic, tectonic and hydrothermal events in the oceans by establishing long-term monitoring facilities on and in the seafloor;
- sampling the lower part of the oceanic crust to determine its composition and the nature of the transition from crust to oceanic mantle;
- developing a general theory for melting and melt transport processes in the oceanic crust and mantle.

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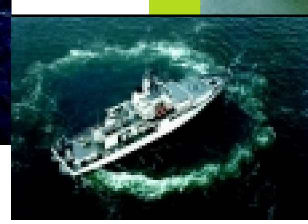
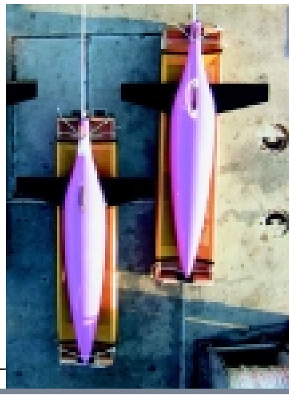
ENABLING PROMISING OPPORTUNITIES FOR DISCOVERY

Ships are mainstays of oceanography, but novel ocean-observing technologies installed and operated on and around them advance the science. New tools include remotely operated and autonomous vehicles, powerful acoustic and photographic imaging and mapping systems, and physical, chemical and biological sensors for making *in situ* measurements. The information revolution permits sophisticated data assimilation—the integration of models and data—leading to the development of more realistic and reliable ocean models. The technological feasibility of using fixed and mobile observing systems together to study changes in the ocean, and on and below the seafloor, has been demonstrated. Enhanced investment for developing the enabling technologies, and carrying out new multidisciplinary, integrated experiments, is critical to advancing our understanding of the marine realm.

ACCESS TO THE SEAS

A substantial, well-coordinated, multi-agency fleet replacement plan is needed to maintain U.S. leadership in seagoing capabilities. Maintaining a modern, well-equipped research fleet is a prerequisite for a healthy and vigorous research program in the ocean sciences. The anticipated mix of research demands large vessels capable of mounting multidisciplinary studies near to and far from land, and supporting remotely operated vehicles and submersibles. Highly specialized vessels such as drillships, which allow sampling deep below the seafloor, and versatile small- and intermediate-sized ships for studying the coastal ocean, will also be required.





NEW TECHNOLOGIES

New technologies facilitate novel experiments and capture new data from the ocean. A vigorous effort in technology development and implementation of new tools and methods in ocean science is justified.

- Solving the problem of ocean sampling on space and time scales appropriately tuned to the processes being investigated is essential. Important oceanographic processes often take place at scales that are difficult to observe and nearly impossible to incorporate in large-scale models. They range from episodic convection or small-scale turbulence to global-scale ocean circulation. New proxy indicators, sampling and observation strategies, and technologies must be developed to adequately measure and understand these processes.

- New fixed and mobile ocean-observing systems complement ships and satellites and must be deployed if critical events are to be observed and studied. No single technological approach can give synoptic, high-resolution or continuous views of the whole ocean or the seafloor below. A new class of platforms offering new research capabilities has recently been made available. Sensors and sampling strategies to optimize the mix of these new platforms with ships and satellites are needed.

- Sustained time-series observations of the ocean are essential for basic research. Extensive, nearly continuous time-series measurements in the oceans are required to understand long-term trends and cyclic changes in the oceans and in global climate and episodic events such as major earthquakes, volcanic eruptions and submarine landslides.

DATA ASSIMILATION

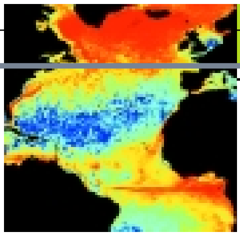
A continuing effort must be made to improve databases and to provide the scientific community and the public ready access to them. The continued improvement in the techniques and mechanisms by which data are collected, controlled for quality, made available, analyzed and archived must go hand in hand with oceanographic research and with developing and deploying new ocean monitoring systems. Rapid data assimilation is also critical to developing and using predictive ocean models that are continuously updated with synoptic observations.

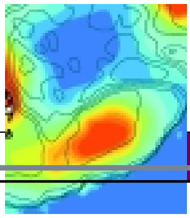
MODEL DEVELOPMENT

The development of models with multiple applications is a priority. A special effort is needed to develop models that link different parts of the ocean system. Linked models that tie together physical, geological, biological and chemical systems show great promise and are likely to grow in importance in oceanographic research. Interactions between such modeling efforts and field programs will aid in designing observation strategies and in evaluating outcomes.

PERTURBATION EXPERIMENTS

A new class of controlled perturbation experiments has already provided unique scientific information not available through conventional methods. The controlled fertilization of areas of the surface ocean with minute amounts of iron can be used to study both carbon dioxide uptake and ecosystem dynamics; such experiments constitute a new, large-scale, moving (with the currents) variant of well-known perturbation plots long used in agriculture and ecology—a variant that presents significant challenges in implementation, replication and sampling. The establishment of marine reserves, or sanctuaries, is another perturbation experiment that deserves to be carefully exploited with predictive models and time-series observations.





12 TWELVE

FIGURE
DESCRIPTIONS AND CREDITS

Front Cover. Top: Hurricane Alberto as seen by Quikscat satellite wind fields (NASA, Jet Propulsion Laboratory). **Second From Top:** Sea surface temperature as modeled by a high-resolution model of Atlantic circulation (R. Bleck, Los Alamos National Laboratory). **Third From Top (Left):** Visualization of a thin vertical slice through a laboratory-scale odor plume developing in a turbulent boundary layer (J. Crimaldi, M. Wiley and J. Koseff, Stanford University). **Third From Top (Right):** Computer-generated perspective view of oceanic crust and upper mantle in the Atlantic Ocean (B. Tucholke, Woods Hole Oceanographic Institution). **Bottom:** Contour map of sea-surface temperature anomalies associated with the Pacific Decadal Oscillation (Nathan Mantua, University of Washington, Seattle).

Inside Front Cover: Visualization of a thin vertical slice through a laboratory-scale odor plume developing in a turbulent boundary layer (J. Crimaldi, M. Wiley and J. Koseff, Stanford University).

Page 1. Left: Coastal Zone Color Scanner image, 14 November 1978, during a *Gymnodinium breve* red tide bloom (P. Stegmann and K. Carder). **Right:** Thermophilic subseafloor microorganism (M. Summit, Washington University).

Page 2. Left: Correlation between GISP2 (ice core) oxygen isotope time series and planktonic foraminiferal and ventilation data from an Ocean Drilling Program sediment core recovered from the Santa Barbara Basin (I. Hendy and J. Kennett, University of California, Santa Barbara). **Right:** Estimates of anthropogenic carbon dioxide from the Atlantic basin along a meridonal cross section in the center of the basin (R. Wanninnkhof, NOAA).

Page 3. Left: Hurricane Alberto as seen by Quikscat satellite wind fields (NASA, Jet Propulsion Laboratory). **Right:** Change in salinity at the bottom of the North Atlantic between the 1960s and 1990s (I. Yashayaev, Bedford Institute of Oceanography).

Page 4. Left: Section of tracer concentration and potential density from the Brazil Basin tracer release experiment (J. Ledwell, Woods Hole Oceanographic Institution). **Right:** Visualization of a thin vertical slice through a laboratory-scale odor plume developing in a turbulent boundary layer (J. Crimaldi, M. Wiley and J. Koseff, Stanford University).

Page 5. Left: Bio-Optical Multi-frequency Acoustical and Physical Environmental Recorder (BIOMAPPER II) (P. Wiebe, Woods Hole Oceanographic Institution). **Right:** One of a series of photos taken from the *Alvin* submersible over the course of about six years documenting faunal community development along the East Pacific Rise (T. Shank, Woods Hole Oceanographic Institution; R. Lutz, Rutgers University; and K. Von Damm, University of New Hampshire).

Page 6. Left: A vertical section of measured sea water density downstream of a coastal upwelling jet near Cape Blanco, Oregon (J. Barth, Oregon State University). **Right:** Satellite-derived image of sea-surface pigment obtained during a summer period of active, wind-driven upwelling (M. Abbott, Oregon State University).

Page 7. Left: Chunk of frozen methane hydrate ("burning ice"). (M. Torres and A. Trehu, Oregon State University). **Right:** Photograph taken from the *Alvin* submersible showing a bacterial mat covering a data logger, which was bathed in hydrothermal fluid leaking from the bottom of a borehole seal, or CORK (K. Becker, University of Miami).

Page 8. Left: Schematic drawing of part of the solid Earth cycle showing subduction of the oceanic lithosphere and creation of new continental crust. **Right:** Computer-generated perspective view of oceanic crust and upper mantle in the Atlantic Ocean (B. Tucholke, Woods Hole Oceanographic Institution).

Page 9. Left: D/V *JOIDES Resolution* (Ocean Drilling Program). **Center:** *R/V Thomas G. Thompson* (University of Washington). **Right:** *R/V Cape Hatteras* (Duke University/University of North Carolina).

Page 10. Left: Seaglider autonomous underwater vehicle (C. Erikson, University of Washington). **Right:** . Autonomous Benthic Explorer (ABE) for gathering seafloor magnetic data (Woods Hole Oceanographic Institution).

Page 11. Left: Sea surface temperature as modeled by a high-resolution model of Atlantic circulation (R. Bleck, Los Alamos National Laboratory). **Right:** Climatological distributions of *Pseudoclanus spp.* for March-April derived from ten years of MARMAP observations (number of animals per m^3) (D. McGillicuddy, Woods Hole Oceanographic Institution).

Page 12. Left: Conceptual design of a seafloor observatory to detect and characterize activity associated with an active seafloor volcano (J. Delaney, University of Washington). **Right:** Black smoker along the East Pacific Rise (Woods Hole Oceanographic Institution).

Back Inside Cover. Left: Satellite-derived image of sea-surface pigment obtained during a summer period of active, wind-driven upwelling (M. Abbott, Oregon State University). **Right:** Computer-generated perspective view of oceanic crust and upper mantle in the Atlantic Ocean (B. Tucholke, Woods Hole Oceanographic Institution).

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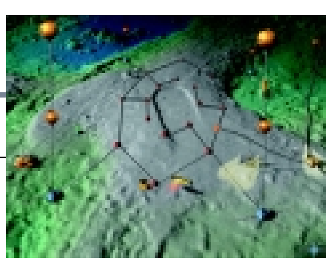

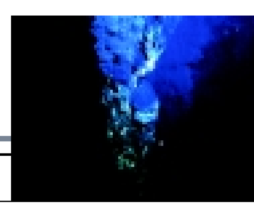

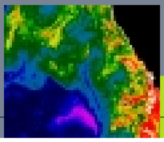

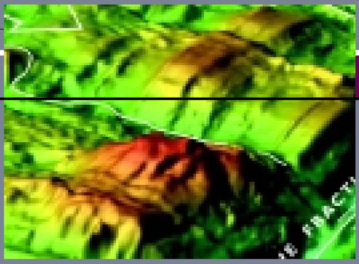

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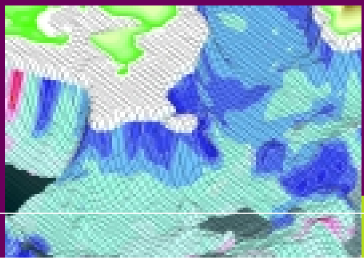
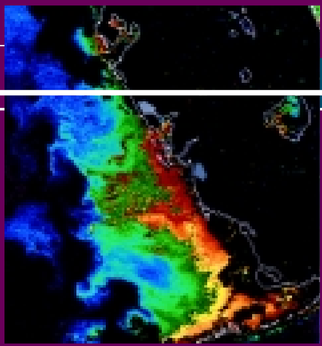
Arlington, VA 22230





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