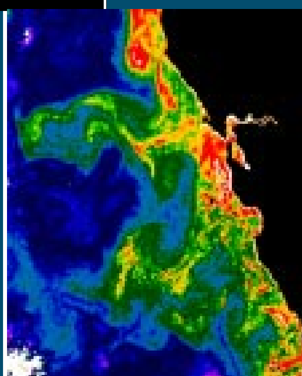
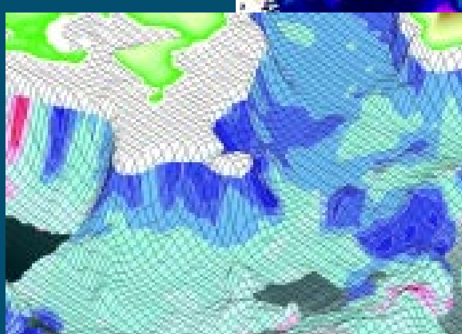
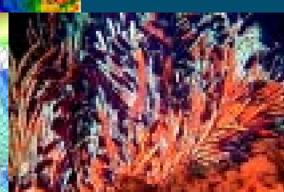
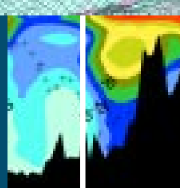


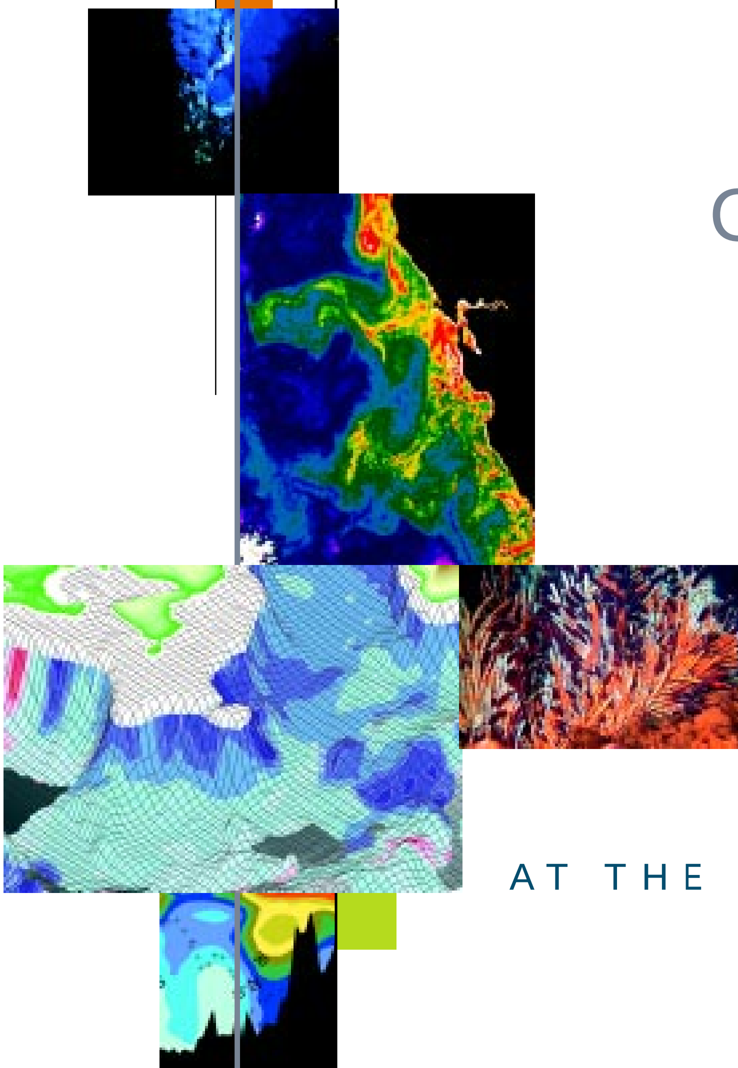






OCEAN SCIENCES

AT THE NEW MILLENNIUM



OCEAN SCIENCES

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* *Decadal Committee Co-Chairs*
** *Ex Officio Member*

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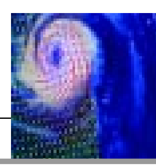
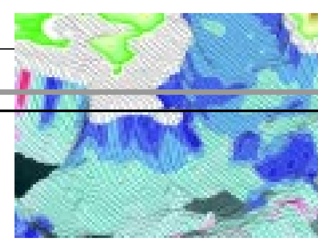
PREFACE

During the summer of 1998, the Director of the National Science Foundation's Division of Ocean Sciences appointed a Decadal Committee to review "the most important and promising opportunities for discovery and new understanding in the ocean sciences over the next decade." The committee's charge proved to be challenging, for the scope, scale and complexity of the ocean sciences have increased enormously over the last few decades. Forcing of climate change by greenhouse gases has emerged from the realm of scientific study into a serious socioeconomic issue, placing stringent demands on understanding key ocean processes involved in the transport of vast quantities of heat and carbon dioxide. Huge new demands imposed by human development pressures and extraordinary impacts on marine ecosystems in coastal regions are now seen as marked changes in the marine environment. The end of the Cold War has forced a reassessment of national marine science priorities.

In addressing the charge, the Decadal Committee sought to draw on the widest possible input from the ocean science community. The committee initially relied heavily on four disciplinary reports covering ocean physics, chemistry, biology, and geology and geophysics, which had been prepared within the previous five years. Because formal participation in the disciplinary workshops was limited, the Decadal Committee solicited by e-mail, and advertisement through the membership of the American Geophysical Union, the views of over 2,000 ocean scientists. Approximately 400 replies were received, many of them quite detailed. These comments factored into the committee's deliberations and, ultimately, this report. The Committee also incorporated community input from a web-posted draft of the report, which was accessed over 3,000 times.





"I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

Isaac Newton

The Decadal Committee established seven working groups based upon public responses and the principal crosscutting themes identified from the disciplinary reports, with the intent of examining the importance of these new areas to ocean science. These working groups were:

- The Ocean's Role in Global Climate
- Long-Term Ocean Observations and Prediction
- Ocean Turbulence
- Non-Equilibrium Ecosystem Dynamics
- The Complex Coastal Ocean
- The Ocean Below the Seafloor: Fluid Flow and Effects on Geology, Chemistry and Life in the Crust
- Dynamics of Oceanic Lithosphere and Margins

This report, "Ocean Sciences at the New Millennium," presents the results of the working groups, and highlights areas where cooperation across traditional disciplinary boundaries is likely to lead to important new insights. These themes are not intended to represent all aspects of the disciplinary science reflected in the individual workshop reports. This report concludes with key findings from each of the working group themes and broad recommendations for future research. The report does not address implementation or cost issues— the committee was specifically asked not to do so—as these are dealt with by science proposals, by NSF program development and by policy decisions within NSF.

This NSF-commissioned report addresses fundamental science issues. It was not possible to address all topics, however, including several that are in common with mission agencies such as NOAA, NASA, DOE and the US Navy, where NSF support often plays a crucial role. In particular, the report does not cover: (1) the technical details of new ocean-observing satellite systems, (2) the design and development of primarily operational systems for very large-scale ocean observations, such as a Global Ocean Observing System, (3) the study of oceans on other planets, (4) marine acoustics studies derived from Navy SOSUS arrays, and (5) direct applications to operational fisheries management.

COMMITTEE CHARGE

The object of this activity is to develop a clear and compelling description of the most important and promising opportunities for discovery and new understanding in the ocean sciences over the next decade. The product will be a succinct (100-150 pp) report written for community and agency readership.

The most challenging task is integration—we need an original vision of the future of the ocean sciences over the next decade presented (as far as possible) as an integrated whole.

The foundation of the report will be the four disciplinary science reports plus, as appropriate, other recent planning documents from special focus programs. But the assumption will not be made that these documents are in fact comprehensive. Efforts will be made to identify gaps and omissions.

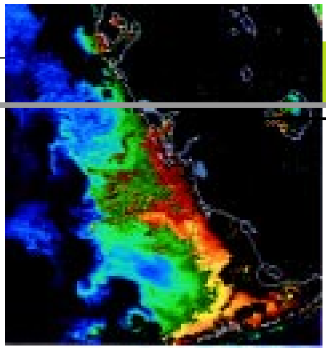
Boundaries with other disciplines will be explored, multidisciplinary efforts will be identified and fully developed.

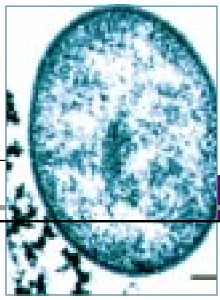
EXECUTIVE SUMMARY

The oceans play a pivotal role in climate, contain the largest and most unexplored habitat for life on Earth and provide routes for commerce and sites for recreation. The oceans also contain important food and energy resources in great demand by society. Movement of the great oceanic plates builds spectacular mountain ranges, but is also the cause of earthquakes and volcanoes that wrench the margins of the ocean basins.

In the decade ahead, ocean scientists are poised to make major breakthroughs in the understanding of ocean biology, chemistry, geology and physics. Such potential has been created by an extraordinary period of invention and discovery from which new capabilities have emerged in the areas of computation, molecular biology, deep drilling and rapid ocean-observing technologies. These new capabilities are providing unparalleled views of the ocean basins, their changing interaction with the atmosphere, the great biological shifts in near-surface waters, and the emerging view of the long-hidden deep ocean basins. The promise of progress in the next decade is predicated on these new tools and the new "look" at the ocean that these tools have made possible.

It has been more than thirty years since a comprehensive survey of the entire field of oceanography has been undertaken. Because the field has changed dramatically in the intervening years, and because of the unmistakable importance of the oceans to our nation, the National Science Foundation's Division of Ocean Sciences formed a "Decadal Committee" to examine the future of oceanographic research over the next decade. The committee was asked to identify the most important and promising opportunities for discovery and new understanding. To carry out their charge, the Decadal Committee initially relied heavily on four disciplinary reports covering ocean physics, chemistry, biology, and geology and geophysics, which had been prepared within the previous five years with extensive community participation.





The Decadal Committee assimilated the material from the disciplinary reports, as well as other community input, and selected seven topics for special emphasis. These broad topics cut across disciplinary boundaries and identify areas where significant progress can be made in understanding ocean processes and their impact on Earth and on society. These topics are:

The Ocean's Role in Global Climate. Scientists have voiced concerns over global warming for over 40 years. Today these concerns have reached a sufficient level of public awareness that they are beginning to be addressed by international policy makers. Plans are now being made for very large-scale changes in our energy industry, yet we have limited knowledge of the complex oceanic lag times and linkages between radiative input and climatic response. Moreover, recent evidence reveals that climate change has occurred within only a few decades in the geologic past in the complete absence of human intervention. Innovative tools now exist for observing, modeling and comparing the climate changes of today with those of the geologic past, and for carrying out novel experiments that test active intervention in the greenhouse gas-climate system.

Long-Term Ocean Observations and Prediction. A program of sustained observations is a requirement for understanding oceanographic processes. The very few existing time-series stations paint a compelling picture of important oceanic changes in physics, chemistry and biology. Yet these stations capture the time domain at only a single point. New strategies for observing the appropriate spatial correlation are required. Deployment of a large number of new stations and efficient tools, such as instrumented floats and vehicles, will greatly enhance our ability to observe and predict important planetary changes. These efforts to extend into the future the detailed records of oscillations in the oceans and in the climate system should go hand-in-hand with efforts to extend them into the past.

Ocean Turbulence. Turbulent mixing in the ocean is a difficult property to observe. Turbulence affects small-scale processes such as scent tracking by microscopic organisms, and large-scale processes such as the formation of dense, cold and deep water in high latitudes and its return flow to the surface through thermohaline circulation. Large-scale tracer injections into the ocean make it clear that the interaction of ocean tides with the seafloor topography induces major increases in mixing rates over those taking place in the ocean's interior. Small-scale studies have permitted insightful numerical models to be constructed that describe animal behavior in a turbulent world. Mesoscale eddies in the upper ocean contain much of the energy, and transport most of the signals, required for ocean understanding, yet their number is too great, and their size too small, for true representation in present-day numerical models. The significant extension of innovative tracer studies, expanding capabilities for numerical simulation, and new sensors, skills and methods for turbulent flux observation all promise important breakthroughs in the next few years.

Non-Equilibrium Ecosystem Dynamics. The realization that marine ecosystems are commonly in disequilibrium represents a major change in the direction of ocean ecological studies. Oceanic populations may naturally show directional changes over time, or oscillate between different states. Many oceanic processes are inherently nonlinear, so that small perturbations at one frequency can cause large-scale changes at another. Today we also have human influences of enormous scale on fisheries and on climate, and these add to an initially complex system. The introduction of exotic species, the proliferation of harmful algal blooms and the effectiveness of marine reserves, are all examples where sophisticated ecosystem knowledge is required. Great progress has been made in observing ecosystem trends, and increasingly in coupled biological-physical observation and modeling. Controlled experiments, for example, adding or removing species from an ecosystem, can now be carried out to test important hypotheses and enhance conservation goals.

The Complex Coastal Ocean. The ocean margin occupies only about 10% of the global ocean area, and a much smaller area of its volume, but it dominates the economic importance of the sea. Almost 50% of the 269 million people in the US live in coastal counties. Material fluxes to the coastal zone are largely unidirectional—from the land to the sea—and these fluxes of sediments, biologically active materials and sometimes toxic compounds are rapidly increasing. If we are to comprehend the impact of these fluxes, we must conquer the complexity of coastal transport processes. The physical forcing of wind provides coastal upwelling, enriching marine ecosystems and creating rich fisheries. Climate shifts can change these dynamics with enormous consequences. The time and space scales of these changes can be small. The need for a synoptic view of this environment to understand the processes that produce these changes presents major challenges for the coastal oceanographer. New eyes from satellites and coastal radar can provide needed observations, and new couplings of biology and physics can illuminate the field.

The Ocean Below the Seafloor. Fluid flow through the oceanic crust, and through the seafloor along the margins of the ocean basins, is the fundamental process by which mass and energy are transferred from Earth's interior to the ocean and atmosphere. With the discovery of hydrothermal vents in the 1970s, it was soon realized that a volume equivalent to the entire ocean is circulated through the seafloor about once every six million years. This "ocean below the seafloor" flows about one thousand times more slowly than the ocean's thermohaline circulation, but it emerges from the seafloor carrying potent fluids with large chemical signals. How this cycle is driven in space and time, and how deep bacterial populations thrive in this flow and change its chemical nature, are important questions. The strange world of hydrothermal fluids is matched by the formation of "frozen" methane gas as a solid hydrate at the ocean margins. Evidence suggests that liberation of enormous quantities of methane from these deposits, by unknown mechanisms, has occurred in the geologic past.

Dynamics of Oceanic Lithosphere and Margins. During the past four decades the ocean basins have been mapped and sampled with an increasingly sophisticated array of tools, enabling scientists to develop and refine the plate tectonic paradigm, as well as discover seafloor hydrothermal vents with their unique biological communities. While we have recently made great strides in spatially characterizing the seafloor, and determining its evolution on geologic time scales, the details of the processes that create and modify the seafloor landscape, and crust and mantle below, still require further investigation. In addition, increasing evidence suggests that mantle dynamics and lithosphere recycling play a role in environmental change and natural resource accumulation. In the distant past, episodic large-scale magmatism appears to have profoundly affected Earth's environment, but the magnitude, history and cause of variations in mass flux from Earth's interior are not well understood. Advanced drilling, sampling and monitoring technologies will enable us to address these fundamental questions.

In assimilating the information in these topics a number of key findings emerged. These indicators of novel science cut across the traditional fields and provide challenges for the decade ahead.

Climate knowledge. An increased knowledge of the oceanic fluxes of heat, water and biogeochemical properties that drive climate, together with a better understanding of the interplay of the internal oscillations of the deep and shallow ocean, are essential for evaluating climate change and for planning how to respond to, or ameliorate, rapid changes.

Physical complexity. The complexity of ocean circulation may now be studied in sufficient detail to permit additional insight on the transport of material, and the fluctuations of ecosystems, important to mankind. One key aspect of this complexity is turbulence, where advances in knowledge will result in new understanding of problems ranging from water mass conversion to predator-prey interactions. Advances in ocean numerical modeling made possible by increased understanding will greatly enhance understanding and prediction on time and space scales important to society.

Climate and shifting ecosystems. A more quantitative understanding of climate-biology coupled fluctuations is required. Interaction of ocean circulation with behaviorally controlled movements of organisms maintains the spatial connections and persistence of marine populations. Rather than hovering about a long-term equilibrium point, marine ecosystems are now thought to be easily shifted to new states by a range of environmental factors. Unless this behavior is well understood, its fundamentally nonlinear character poses significant risks for both intentional and unintentional efforts by humans to manipulate the oceans.

New monitoring systems. Despite increased understanding and technical capabilities, our knowledge of ocean biological, chemical and physical fields does not yet provide an adequate baseline for observing and predicting known changes. It is now possible to create important, new, science-based observing programs that can meet this challenge. Such observing systems could also serve in observing and understanding critically important, abrupt Earth episodes as diverse as earthquakes, eruptions beneath the sea or harmful algal blooms on the surface ocean.

Human impact. The oceans play a key role in the emerging study of the links between climate and human health. An opportunity exists to greatly increase our knowledge of pathogens and parasites in the ocean and in identifying, predicting and ameliorating their impact on human health and the health of marine ecosystems. There is clear evidence of the human impact on water, chemical and sediment fluxes to the oceans that now equals or exceeds the fluxes of nature. Increased knowledge of the links at ocean margins is essential for guiding human development in coastal regions.

The subseafloor and life at extremes. Advances in geophysical imaging, geochemical tracing and geodynamical modeling, coupled with the renaissance of deep ocean drilling technologies, will lead to major breakthroughs in understanding Earth's dynamic evolution. Fluids flowing through the seafloor influence a wide range of microbial and geological processes. Evidence for the existence of bacterial communities deep below the seafloor is an exciting indication of the extremes of life. The nature and extent of biological activity within oceanic crust, the role of these fluids and contained biota in geochemical cycling between the solid Earth, hydrosphere and atmosphere, will be an important new avenue of research in the coming decade.

OCEAN ECOLOGY: UNDERSTANDING AND VISION FOR RESEARCH (OEUVRE)

The OEUVRE report (1998) reflects 30 years of impressive progress in biological oceanography and marine ecology and anticipates further progress through four broad themes. The OEUVRE report also notes a blurring of distinctions between biological oceanography and marine ecology and adopts "ocean ecology" as the umbrella term covering marine ecological research. Among other potent forces leading to unification are broad adoption of molecular and genetic methods to identify the biological units being studied and their genetically programmed activities, and the universal appreciation by oceanographers and ecologists of the importance of fluid dynamics to biological processes at all scales and levels. Methods and experimental designs have migrated rapidly in both directions between ecology and oceanography, with manipulative chemical experiments now carried out on a grand scale and flow dynamics measured and simulated on many scales in many ways by oceanographers and ecologists alike. Ocean ecology is so broad, however, that the OEUVRE report intentionally does not try to review or predict it all. One potentially serious compromise made in selecting participants and discussing the future, in order to cover as much of the subject area as feasible, was to emphasize questions and de-emphasize technologies. From this perspective, the four major themes did not cover everything, and progress will certainly follow other courses as well. These themes, however, were clearly good choices to represent the depth and diversity of the field as is perhaps best demonstrated by remarkable progress on all four in the short years since the OEUVRE report was written.

Functional significance of biological diversity in biogeochemical dynamics. A primary scientific problem in building quantitative "box" models is finding a suitable level of aggregation. The extreme approach of treating each species as its own "box" in the system is not yet feasible. Notably, many microbes now identified using molecular genetic methods have never been cultured, and the geochemical transformations that they accelerate are unknown. On a macroscopic scale, no one knows how the hundred or more species of sediment-feeding animals in some deep-sea and tropical benthic communities differ functionally. Traditional compromises of aggregating into boxes defined by trophic levels and body sizes are being challenged and improved in at least two ways. The more obvious way is via molecular genetic methods that can identify organisms by their genetic structure, map genetic structure on molecular function (e.g., presence of a nitrogenase gene), and analyze for current level of activity (e.g., through rate of transcription into RNA and production of proteins). The less obvious means is through empirical experiments, often in microcosms, with systems that systematically vary in species diversity. The latter approach continues to reveal rich feedbacks that make predictive understanding so challenging.

Adding to the challenge of defining boxes and flows in models is that the problem is not purely biological. How will changes in the physical, geological and chemical environment, for example, resulting from climate change, alter activities of organisms that are present or modify the species list? In addition to the problems posed by the interdisciplinary nature of such questions are important sampling issues such as how best to resolve the biological diversity within and below the seafloor and to plumb its physiological responses to environmental variables.

Functional ecology (of individuals, with ramifications for populations, communities, and ecosystems). Behavior and performance of individuals as a function of environmental parameters and neighbors are the purview of "functional ecology." It is not unusual for an individual marine organism to span four orders of magnitude in length during external development from egg to adult, and development entails a transit from Reynolds numbers far below one to Reynolds numbers far above one. Furthermore, biomechanical, biochemical and other approaches quickly reveal that larvae and juveniles are not simply scaled-down versions of adults. Completion of a life cycle in the sea often entails at least three distinct foods: a larval food, a young juvenile food and an adult food. Not only are the food cues different, but the hunting strategies often are vastly different because of the transition from laminar to turbulent flows.

A major advance of the last 30 years is the revelation that a little turbulence is a good thing for many suspension feeders, as it renews the local concentration of food and brings new items into the sensory arena of the suspension feeder. Too much turbulence, however, interferes with particle detection, capture or both. Turbulence poses sensory issues for organisms as small as bacteria, as successful search strategies for solute concentrations must take the behavior of local solute concentration in this intermittent, three-dimensional flow regime into account. The study of chemosensing in particular is poised for major advance. New capabilities to predict chemical behavior from molecular structure cut through the combinations and permutations of molecular structure that otherwise would need to be tested. Analytic capability for trace quantities also has exploded.

A challenge of the next decade is to discover what sensory information organisms combine, and in what ways they combine it to determine their interactions with other organisms and with the nonliving portions of their environments. How does biomechanical resistance to damage change with growth in size of a kelp? What is the smallest bivalve pump that is effective in suspension feeding on phytoplankton? Over what time scales does previous feeding history influence present feeding behavior as organism size changes? To what extent do functional responses happen at particular times, stages of development or achieved body sizes?

Structuring dynamics of biological assemblages. It is clear that many marine species exist in metapopulations; local populations experience export and import of offspring to and from other populations. Because flows in the sea are so strongly time varying, however, it is not clear for most local populations to what extent they are maintained by local reproduction or by reproduction "upstream." And the answer typically varies from one year to the next. This information is critical in rational design of marine preserves, so initial preserves must play a role as manipulative experiments to help determine the answers. Molecular genetics continue to surprise. Organisms with obvious dispersal stages nevertheless can show strong local relatedness; they can, but do not, disperse. Conversely, genetic structure of some planktonic foraminiferans at both poles is identical, implying recent exchange. So few systems have been well worked out that empirical generalizations cannot yet be expected, but both scientific curiosity and the need for conservation practice grounded in understanding of ecological mechanisms can be expected to fuel advances over the next decades.

Determining that some "keystone" species are inordinately important in affecting community structure is one of the great ecological successes of the last three decades, but predicting which species would have strong interactions has been an elusive goal. Recent successes in prediction have taken the opposite perspective, that interactions become strong when multiple, weak interactors are missing, and point to the importance of inconspicuous food-web interactions that may not have received enough attention previously (e.g., omnivory).

Human impacts and habitat linkages. The most sobering aspect of the OEUVRE workshop was the realization that little if any of the ocean is unaffected by the present or past activities of humans (e.g., whaling and release of salmon from hatcheries as well as more obvious pollution). In other words, mankind is doing many manipulations without understanding their consequences. A corollary is that a greater effort needs to be devoted to taking advantage of those manipulations to uncover consequences and mechanisms. Experience with science shows that a good method is to predict those consequences and then learn from the errors in the predictions as the perturbation proceeds. These approaches need to be iterative, interactive and bold to give any hope of learning faster than the rate of anthropogenic change. For example, attempts should begin immediately to alter the course of harmful algal blooms rather than simply study them without intervention. Even without anthropogenic influence, community structure has changed continually in the sea and elsewhere, but the rate of change clearly has been accelerated by human activities. Both ice caps appear to be shrinking, and a northwest passage of open water may have dramatic biogeographic consequences. Teasing apart the causes of community change has arguably been most successful from time series, and the need to have marine time series extended into a domain less influenced by mankind argues for greater use of fossil evidence. Molecular tools are already helping here, for example, to reveal that the dextrally and sinistrally coiled forms of *Globigerina* used as paleotemperature indicators are genetically distinct. Even when morphological differences are less obvious, genetic evidence of distinct populations can often help to establish morphological characters of use in the fossil record. Further, studies of functional ecology should help to reveal the functions of spines and other characters recognizable in fossils, giving more direct indication of environmental features during life. Because fossils are preserved in nearshore environments for only limited periods, rapid progress is essential.

FUTURE OF MARINE GEOLOGY AND GEOPHYSICS (FUMAGES)

The vastness of the world's oceans, and their considerable average depth of 4 km, pose great challenges for those who probe oceanic lithosphere. Using tools such as high-resolution sonar systems, drillships, mass spectrometers, microprobes and multichannel seismic systems, marine geoscientists have put together a remarkable array of discoveries. As a first step in the discussion of the Future of Marine Geology and Geophysics (FUMAGES), attendees of the 1996 Ashland, OR workshop examined some of the most exciting scientific advances in their field in the last 20-25 years.

Detailed mapping and sampling at mid-ocean ridges, and more recently some longer-term experiments, illustrate the complex relationship among biology, chemistry and physics in the ocean. Seawater flushing through the mid-ocean ridge system pumps a variety of elements, vital to vent communities and the ocean's overall chemical budget, into the oceans as well as large amounts of heat. Microbial communities, discovered both in the shallow crust at mid-ocean ridges and at depths of up to 800 m in seafloor sediments, may have implications for the origin of life on Earth and the potential for life on other planets.

Over the past 20 years, paleoceanographers, by measuring isotopes of elements such as oxygen that are bound into the shells of microscopic organisms, have linked orbital forcing to Pleistocene climate change. Paleoceanographers are finding evidence for millennial, even centennial, variability in the ocean-climate system. With the data in hand, they are beginning to make model/data comparisons which have shown, for example, that sea-surface temperatures were cooler during the last glacial maximum.

Marine geophysicists have made great strides in studying the kinematics and geodynamic implications of plate tectonics. They have determined the kinematic history of all major ocean basins, and have developed a robust model for the variation of seafloor depth with age. New insights have been gained into the mechanics of continental rifting and rift-related magmatism. Large-scale seismic experiments and detailed mapping of discrete mid-ocean ridge segments have greatly enhanced our knowledge of ocean crustal generation processes. Processes that cannot be explained by plate tectonics have also been identified.

Major advances have been made in the study of processes controlling sea-level change. By systematic studies of both academic and industry seismic profiles, sea-level changes on regional and global scales have been correlated. This "sequence stratigraphy" provides a unifying framework in which all the components of a sedimentary facies can be compared, correlated, and perhaps reevaluated. A conclusion from these studies is that few crustal margins are truly stable, and that local sea-level behavior is a function of many factors.

Promising New Areas of Research

Following presentations on scientific highlights, workshop participants were divided into four thematic groups: Solid Earth, Paleoceanography, Sediments, and Fluids, where future research directions were discussed. Some common themes came out of these discussions, and below are excerpted from the FUMAGES report.

- **Exploration of the fourth dimension (time) through in situ measurements of active processes on various timescales from seconds to decades.** The geologic record contains evidence of many catastrophic events, for example, earthquakes, landslides, and volcanic eruptions. Most of our models, however, smooth these events over time to create steady-state representations for what are really discontinuous processes such as erosion of headlands, glacial meltwater pulses, creation of oceanic crust, and filling of flexural moats. Such steady-state models distort the true impact of these events on human timescales and are useless for hazard mitigation. Given the current lack of understanding of the temporal and spatial pattern of most geologic events, we require the technology to install undersea observatories and event-detection systems to catch geologic events in action.

- **Characterizing and modeling geosystems with complicated, nonlinear responses (e.g., climate, seismogenesis, sediment dynamics).** Many of the research topics central to marine geology and geophysics address the issues such as climate change, coastal pollution and erosion, and earthquake hazards. In some cases, there has been pressure to implement solutions to these problems without a complete understanding of these complicated systems. Some of these systems are now known to be highly nonlinear, such that the input at one frequency can produce a response at very different frequencies. Human forcing may in fact lead to very unpredictable and undesirable consequences. An important area of future research will be in characterizing and modeling systems in which the input forcing is known or can be measured, and the system response can be inferred from the geologic record (geologic time scales) or from direct observation (human time scales).

- **Determining the central role of fluids (water and magma) as agents for geochemical cycling between the solid earth, hydrosphere and atmosphere.** Geologic modification of Earth is controlled by fluids, whether it be in fault zones, magma erupting on a mid-ocean ridge or island arc, plumes rising from the deep Earth, hydrothermal circulation in ocean crust and sediments, or methane deposits on continental margins. These fluids determine the locus of geological activity and are the agents for geochemical cycling between the solid Earth and the hydrosphere and atmosphere. Quantitative understanding of the physical and chemical processes that lead to concentrations and focusing of these fluids through the lithosphere, igneous crust, and sediments until their eventual expulsion into the water column or atmosphere, however, is in its infancy. We need to better understand the physical properties of the medium through which the fluids flow, the stresses acting on these systems, and their chemical, mechanical, and thermal interaction with their host rock.

- **Exploring the role of biological activity on geological processes.** Just as ocean chemistry cannot be understood without taking into account biological cycling of materials, the solid Earth is modified by biologic activity from the scale of bacteria to humans. Submarine ecosystems harbor some of the most unusual and extreme examples of life on Earth, and the implications of understanding how these systems have adapted to and how they modify their environments have implications for the origin of life itself. Links between biologists and geoscientists must be strengthened, and hybrid scientists trained, to make progress in this exciting new area of exploration.

- **Investigating the long-term variability of geological processes.** A glance at the recent past shows a climate system principally forced by the eccentricity of Earth's orbit. Present-day nearshore sedimentary sequences reflect flooding of the world's shelves following the melting of large continental ice sheets, and today's seafloor volcanic activity is completely dominated by steady-state formation of new crust at the mid-ocean ridge. However, with the benefit of the geologic record, we see that just one million years ago variations in Earth's tilt were more important than eccentricity in modulating climate. During glacial maxima, sediment bypassed many continental margins through a series of canyons. In the Cretaceous, plume-type volcanism was far more important than today in the mass and energy transfer between the deep Earth and the surface. While in some cases the causes of the changed in the geologic record are easily identified (e.g., rising sea level), in other cases they are not. More emphasis in the future will be directed toward the documenting the various different stable states of Earth's systems, discovering what events trigger evolution from one stable state to another, and identifying the linkages between the states of very different systems (e.g., climate and tectonics).

To make significant progress in these research areas, workshop participants listed several different tools and technologies that need to be made available to the community. These include: (1) ocean observatory systems (buoys, cables, AUV) and sensors for real-time monitoring of ocean processes; (2) ocean drilling platforms, including one with well control, for sampling Earth's lithosphere and conducting experiments; (3) submersibles, ROVs, and AUVs; for sampling and ground-truth; (4) geophysical imaging tools (3-D MCS, BBOBS, etc.) for deep geophysical imaging of the lithosphere; and (5) Altimetric Geoid. We also need to address the needs of those working near the shoreline in shallow-water, high-energy environments where technology for imaging, sampling, and monitoring is currently lacking.

ADVANCES AND PRIMARY RESEARCH OPPORTUNITIES IN PHYSICAL OCEANOGRAPHY (APROPOS)

Forty-six scientists attended the 1997 meeting on the Future of Physical Oceanography in Monterey, California. Attendees were asked to consider the most significant advances over the last twenty years and the most promising opportunities for the future. Key advances identified by the group include: the revolutionary understanding of the tropical ocean-atmosphere coupling that has lead to the predictive El Niño models, a theoretical understanding of the subtropical thermocline, the estimation of the global distribution of mesoscale variability, the theory and observation of coastal-trapped waves, completion of the World Ocean Circulation Experiment (WOCE) and its accompanying knowledge of the pathways and time scales of ocean circulation, substantial advances in our understanding of bottom boundary layer physics, quantitative measurements of the strength of small-scale ocean mixing and the dependence of this mixing on the strength of the internal wave field. Additionally, technological advances have allowed us to observe the ocean on a broad range of space and time scales. Long-term mooring technology, satellite remote sensing, microstructure probes, acoustic Doppler current meters, acoustic tomography, freely drifting floats and many other innovative instruments and techniques have given us new views of the ocean. For example, the successful TOPEX/POSEIDON mission has mapped sea surface height to 3 cm accuracy at 7 km spacing for 5 years. This advance permits direct measurement of the water movements that characterize the El Niño-Southern Oscillation, as well as permitting global estimates of sea level rise.

While the last twenty years have seen great advance in our physical understanding of the ocean, the field is just beginning to assemble the elements necessary to achieve a comprehensive understanding of the physics of the ocean. In assessing the key areas in which a compelling case can be made for progress, the APROPOS group selected eight themes.

Climate. The problem of climate prediction is perhaps the most difficult issue facing ocean physicists today. The issues surrounding atmospheric greenhouse gas forcing are now well known in general, but in detail there remain huge challenges. Unlike the linkage between equatorial ocean processes and El Niño, where well-identified theory and linear wave guide dynamics provide cohesion, the global climate problem requires an understanding of high-latitude convection and water-mass formation, coupling of the wind driven and thermohaline circulation, the extratropical climatic oscillations, and the physics of air-sea exchange. The decadal time scale of extratropical dynamics means that scientists see only a few realizations of the system within their lifetimes. Thus, to aid our understanding of the ocean's role in our global climate we must expand our database and frame hypotheses about past climate change and ocean circulation using paleooceanographic studies.

The hydrologic cycle. The ocean's role in the global hydrologic cycle is a critical area for study because it impacts the climate system. Our knowledge of the oceanic fresh water source-sink distribution is far poorer than our knowledge of the source-sink distribution of heat. Yet, salinity and temperature contend in their joint effect on the density of seawater and in their influence on the ocean circulation and the climate system. Knowledge of the freshwater input from continents, precipitation and sea ice is poor. Observational techniques addressing these issues (e.g., the use of oxygen isotopes and tritium/helium to diagnose fresh water sources) herald progress. In addition to the development observational techniques, advances on such issues as temperature-salinity relationships, thermocline maintenance and interhemispheric water-mass exchanges are critical to deciphering the ocean's role in the hydrologic cycle.

Observing the ocean. Because the problem of sampling the ocean adequately is enormous, the ocean has traditionally been undersampled, and remains so. However, great strides have been made in the past few decades. Satellites can now observe the ocean's surface, and buoys and floats can drift over vast distances with the ocean currents. Because drifters and floats can now be deployed in large numbers at reasonable cost, they promise to revolutionize data acquisition for physical oceanographers. While future developments in satellite oceanography hold great promise for increasing accuracy, in situ observations will remain critical to our studies. A national effort to support sustained high-quality global observation over decades is needed. Measurements of air-sea fluxes of heat, fresh water and gases, surface and subsurface temperature, salinity and velocity, are all necessary to meet new scientific challenges. Given the rapid increase in Lagrangian measurements by drifting and profiling floats, and a parallel increase in geochemical tracer data, an intense approach to Lagrangian analyses of advection and diffusion is needed. Time-series stations are still very few in number, but where these data are available they show clear evidence of important change, and with modern technology far more observations can be made economically. The TOGA-TAO array of equatorial Pacific buoys is one example of an effective measurement network, and this concept can be greatly expanded.

Global and regional connections. The mechanism connecting the physics of large-scale and small-scale processes in the ocean is not well understood. Transitions from a coastal source to a basin scale signal, from regional signals to global, from wetlands and estuaries to rising sea levels, and from a tropical El Niño to mid-latitude precipitation, are all examples of connections crossing scales. If we can comprehend and capture the physics underlying these transfers we can make important contributions.

Cross-shelf transports. The strongest ocean currents along coasts are those parallel to the shore, which can move material great distances. Yet the strongest gradients in properties are often those across the continental shelf. These cross-shelf transports are often inhibited by topography, and by river outflow. This exchange needs to be understood if we are to address issues such as the control of biological productivity in the coastal ocean, or the removal of contaminants from the nearshore zone. How the ocean couples to its surroundings on both the landward and seaward sides is a critical issue in coastal oceanography. Estuarine processes are important for determining the quantity and quality of terrestrial material that reaches the open shelves. The oceanic setting, including eddies, filaments and boundary currents, in turn determines how effectively coastal influences can spread offshore. Thus, the future study of the continental shelf demands consideration of both offshore and nearshore (estuarine and surf-zone) dynamics.

Inland waters and environmental fluid dynamics. Inland waters such as lakes, rivers and estuaries are of critical importance to mankind, and often yield to the same discipline of observational and computational technologies that promise progress for the open ocean. Here there are exciting opportunities for interdisciplinary work, and lakes often provide model systems for studies of turbulence and topographic forcing.

Turbulent mixing and unexplored scales. Ocean turbulence measurements, essential to understanding the mixing processes by which energy is transferred at different scales through the water column, and by which chemical signals are distributed, are poised for a breakthrough. Ocean physicists have grasped many of the processes important on longer time and space scales, yet they are largely ignorant of the processes on scales of about 100 m to 50 km — a critical scale for many biological processes. Innovations in both theory and measurement are rapidly emerging. These same scales, which characterize the complex ocean physics at coastal boundaries where topography generates instabilities and cross shelf transport, are of key importance. Modern towed and autonomous vehicles offer the chance to explore horizontal scales far shorter than that traditionally sampled by the stopping and starting of a ship. It is these scales, typically ranging from the mesoscale (50 km) to the microscale (less than 10 m), that are important for biological processes and for providing critical physical linkages in mixing.

Numerical modeling as an integrative tool. Large-scale computing is an essential tool for modeling the ocean-atmosphere system. Models represent ways to capture data, and to give expression to theory. The ocean contains important circulation features — the mesoscale eddies — that are 100 times smaller than the equivalent atmospheric features, and thus explicit resolution of these dominant elements is a huge problem and is only currently only marginally possible. Adding to this difficulty is the need to characterize such features as deep convection at high latitudes, topography, and boundary currents. Enormous progress has been made, but as computing capacity and model skill grows we may expect tremendous progress in both understanding and prediction.

THE FUTURE OF OCEAN CHEMISTRY IN THE US (FOCUS)

Ocean chemistry provides insights into oceanic processes at molecular scales, but has an impact well beyond this. There is a consistent history of development of chemical understanding of the oceans followed by application and transfer of techniques into other fields. Ocean physics has come to depend on a variety of chemical tools, beginning with accurate salinity determination and equations of state, and progressing on to the measurement of extraordinarily low concentrations of water-mass tracers. Understanding ocean biological productivity patterns has depended on the evolution of chemical measurements; early macronutrient measurements at 10^{-6} moles per liter explained many first-order phenomena, and more recent assays of ultra-trace nutrients at 10^{-10} moles per liter are beginning to elucidate longstanding and perplexing problems in plankton distributions. Measurements of even lower levels of various elements and isotopes have enabled development of tools critical to the understanding of the ocean's geological evolution.

The FOCUS report reviewed these impacts over the past three decades and previewed new ones to come. The report evolved from a meeting in 1998, attended by more than 50 scientists and program managers, with input from the entire ocean science community. The progress review covered Biogeochemical Cycles, Ocean Sources and Sinks, Gases, Ocean Paleochemistry, Physical Chemistry of Seawater, Sedimentary Processes, Organic Geochemistry, Anthropogenic Impacts, Ocean Ventilation and Circulation, and Analytical Techniques. This review made clear the enormous strides achieved in ocean chemistry over the past three decades.

Biogeochemical studies have sought to unravel the enormous complex of chemical transformations that occur while organisms fix chemical substances into biomass, move them about in the ocean as a result of biological and physical imperatives, and either return to the ocean water as dissolved substances or become buried into the sedimentary pile below. A plethora of biogeochemical processes provide both controls on the abundance of life and revelations about it. New techniques in chemical characterization, often on materials at concentrations lower than have been measured before, have revolutionized our ability to interpret chemical distributions. Molecular forms, such as linkage of metals to organic compounds, dictate element reactivity and govern their ability to modulate processes such as biological production.

Similar characterization skills have facilitated interpretation of environmental change in long records of ocean history recorded in sediments, using an emerging array of tracers that exploit elemental, isotopic, and biomolecular tags. The historical records thus unearthed have provided ancient "experiments" in climate change, such as the "hothouse" and "snowball" Earth. These records have led to important insights into the implications of the present "experiment" in greenhouse-gas buildup.

The ocean's boundaries connect it to land, the atmosphere and the lithosphere. Each of these adjoining environments exchanges chemicals with the ocean, providing vital links in global chemical cycles. These exchanges modulate processes within the sea and, reciprocally, allow the sea to affect processes in its neighbors. Assessing the magnitudes and pathways of these exchanges has occupied much attention and will continue to do so. Particularly exciting discoveries have arisen in these studies at interfaces. For example, discoveries at hydrothermal zones resolved longstanding problems of input-output budgets in the oceans and provided a basis for understanding the spectacular new ecosystems and mineral deposits found there. Studies of atmospheric fluxes yielded an ability to measure extraordinarily low concentrations of chemical tags, such as natural helium isotopes or anthropogenic freons, that reveal the ventilation of the oceans. Combined studies of biological and chemical processes in sediments revealed the intense processing occurring in very small volumes, with major influences on the water column above. Chemical measurements of human-derived materials have demonstrated patterns and impacts of human activity on the oceans, such as the nutrient effluxes that lead to low-oxygen zones in coastal areas; the budgetary approach of chemical oceanographers has been crucial in assessing limits on these dynamics.

The FOCUS process sought to unfetter deliberations from classical, chemical subdisciplines by assessing oceanic processes that occur at various timescales. The ensuing report envisions rapid progress in several areas, driving from combinations of recent discoveries, new paradigms, new technology and new integrations with other fields.

- **The role of plant nutrients in supporting life.** Subtleties in nutrient dynamics and chemical forms, such as small amounts of silica or appropriate forms of trace metals, have profound ability to influence the community structure of plants and the ensuing food web. The ocean's ability to support life and the role of life in maintaining the chemical constitution of the ocean are strongly affected by these nutrient cycles. Emerging analytical technologies and field-deployable sensors will show how these dynamics affect end states of great importance, such as fisheries and harmful algal blooms.

- **Land-sea exchange at the ocean margins.** Margins influence oceanic biogeochemical cycles much more than their small proportion of oceanic area - ca. 10% - might imply. Their proximity to land makes them especially susceptible to anthropogenic influences, resulting in increasing instances of altered nutrient cycling or even redox conditions. Processes that occur disproportionately in margin environments, such as organic matter burial, mineral formation, and denitrification, affect the oceanic balances of many elements. Unraveling the highly variable complex of chemical, physical, geological and biological linkages in margins will provide needed context for the continuing human colonization of the coastline.

- **Organic matter assemblies at molecular and larger scales.** Organic matter affects many oceanic processes more strongly than its low concentrations might imply. The "micro-architecture" of the organic assemblies — the manner in which well-known biochemical compounds are held together — is poorly understood. However, these architectures appear to control organic matter reactivity, with important implications for biological productivity, photochemical processes, mineral formation and trace-metal dynamics.

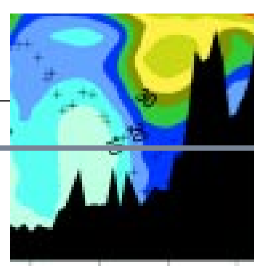
- **Advective chemical transport through the ocean ridges and flanks, ocean margin sediments, and coastal aquifers.** Fluid flow through these environments appears to have greater importance than previously believed, and may strongly influence many oceanic chemical cycles. For example, groundwater input to the ocean is not a large fluid flux relative to river input, but its composition differs so greatly from that of surface waters that it may have very important impacts upon entry into seawater. Greater understanding of the magnitude and variability of these advective flows will improve budgeting of chemicals in the oceans and elucidate many regional processes affected by the flow, such as nutrient inputs.
- **Air-sea exchange.** Gases that directly influence global ecosystems, such as CO_2 and other greenhouse gases, halocarbons that affect stratospheric ozone, and gases that create sulfate aerosol all have important source/sink terms in the oceans. New technologies, such as deliberate tracer releases in the ocean, are rapidly bringing us closer to understanding the limiting factors in gas exchange. More accurate determination of air-sea fluxes of these gases, of both natural and anthropogenic origin, are critical for assessing processes affected by these gases.
- **Material export from the upper water column.** Relationships among mixing, photosynthesis and internal recycling affect this export. Long-term, time-series observations are already radically changing our views of export that were derived from previous expeditionary approaches to measurement. Our understanding of processes such as CO_2 and N_2 sequestration from the atmosphere and pelagic-benthic coupling are thus critically dependent on improving our understanding of euphotic zone recycling.
- **Controls on the chemical and isotopic compositions of sedimentary phases.** Further development of paleoenvironmental indicators, or "proxies," will lead to a better understanding of past climatic and carbon-cycle variations. New analytical technologies, enabling measurements of very small masses in materials that have been already separated according to criteria such as molecular structure, will continue to provide new proxy measurements of former oceanic environments. Earth historical records provide an invaluable guide to natural variability of the chemistry/climate system at various time scales, including natural "experiments" in which the whole system has responded to a perturbation.

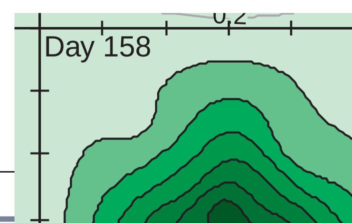
Comparison of these areas for future progress with the headings of the past progress reports shows nicely the maturation of this field and its merging with other fields in ocean science. The FOCUS report also explores recommendations for changes in research infrastructure and education that will enable this anticipated progress to develop.

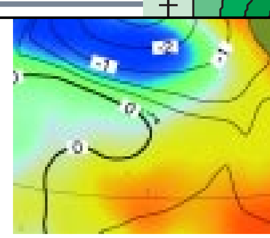
THE OCEAN'S ROLE IN GLOBAL CLIMATE

One of the most pressing environmental challenges that the Earth, ocean and atmospheric science communities face today is to understand how our global climate evolves on decadal and centennial time scales. While many subfields within Earth, ocean and atmospheric science have matured over the past fifty years, the study of our climate and its evolution is still in a period of relative infancy. A main reason for this lag is the relative absence of long time-series measurements and, because climate studies are inherently interdisciplinary, the few time series that exist contain incomplete or inadequate data to answer the complex questions now being posed. An understanding of how Earth and its fluid envelope store and transport heat, carbon and other climatic tracers involves an understanding of biological, chemical, physical and geological processes. The intersection of these fields presents the biggest challenge to climate scientists, but also the biggest potential payoff. The economic and societal benefits that will accrue from an improved understanding of our climate and its change cannot be overstated.

Ocean scientists have a huge role to play in deciphering our evolving climate because of the ocean's importance in establishing that climate. The ocean contains more than 50 times the amount of carbon dioxide than the atmosphere, and the heat capacity of the ocean is more than 1000 times greater than that of the atmosphere. Thus, the ocean acts as the great flywheel, or modifier, of climate. In addition to its importance as a reservoir of carbon dioxide and heat, oceanic circulation, either through large-scale currents, mesoscale motions or diffusive processes, is responsible for the distribution of heat, freshwater and carbon dioxide that are gained from atmospheric exchange. This distribution plays a critical role in establishing global climate. For example, the ocean's poleward transport of heat makes it an approximately equal partner with the atmosphere in regulating the global temperature. Such distribution also makes possible the sequestering of heat and carbon in the deep ocean and in sediments.







As a major heat and carbon reservoir, the ocean acts to modulate the atmospheric response to the anthropogenic input of CO_2. The ocean's heat capacity has reduced the current impact of global warming by creating a lag time of about 30 years between the perturbation of a greenhouse gas concentration in the atmosphere and the full effect of its warming. Figure 1 shows that each ocean basin has warmed significantly over the past 50 years. While this warming extends to nearly 1000 m globally, in the North Atlantic the warming extends to 3000 m, illustrating the importance of the thermohaline circulation in carrying climate signals to the ocean depths. Additionally, because the ocean is such an enormous heat sink, the rate at which the ocean warms in response to increased radiative input has a direct and significant impact on the warming of our atmosphere.

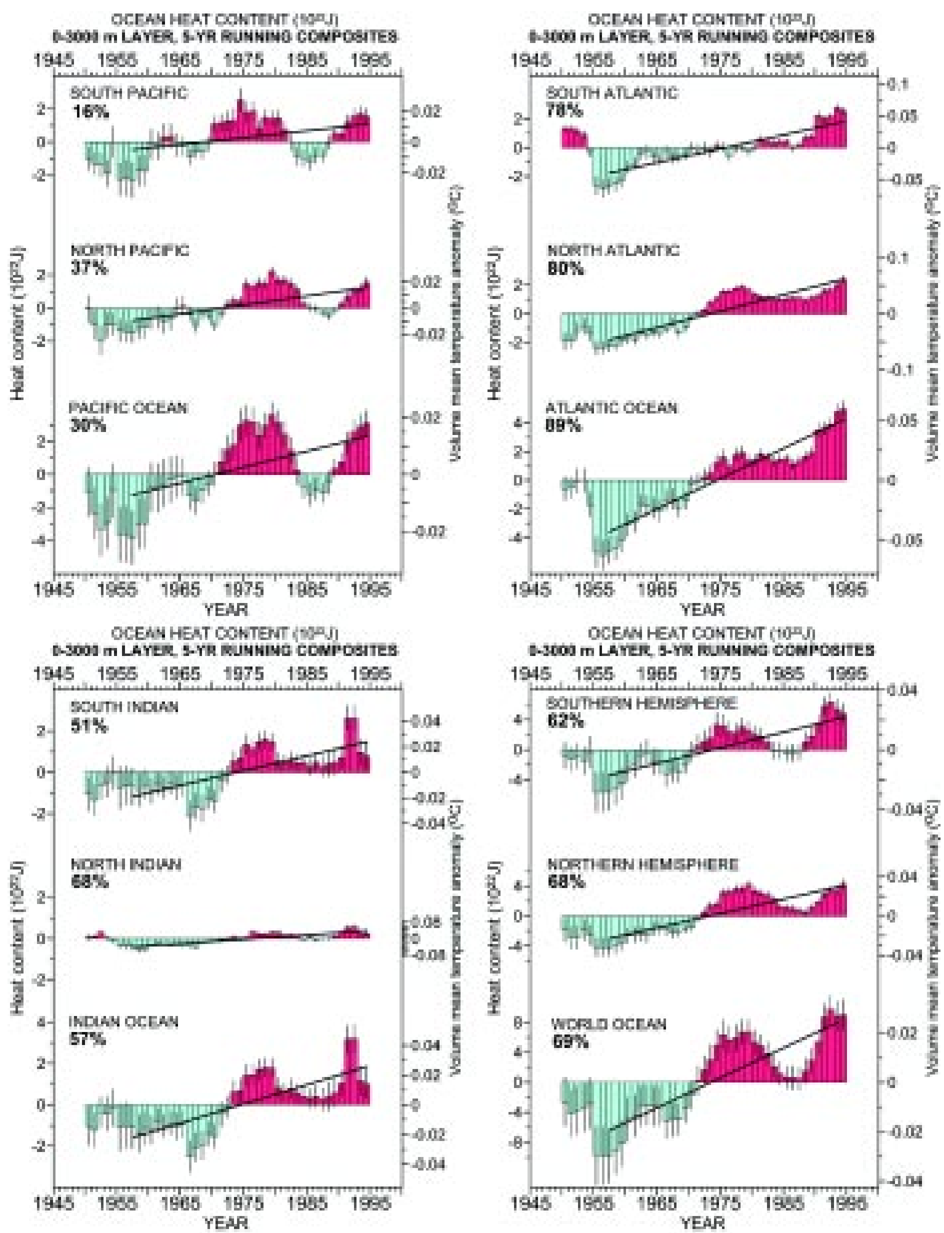


Figure 1. Time series of five-year running composites of heat content (10^{22} J) in the upper 3000 m for each major ocean basin. Vertical lines represent the ± 1 SE of the five-year mean estimate of heat content. The linear trend is estimated for each time series for the period 1955 to 1996, which corresponds to the period of best data coverage. The trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel. Reprinted with permission from S. Levitus, I. Antonov, T.P. Boyer and C. Stevens, Warming of the world ocean, *Science*, **287**, 2228, 2000. Copyright 2000 American Association for the Advancement of Science.

The ocean takes up, by gas exchange with the atmosphere, about 40% of the CO_2 emitted to the atmosphere each year. The rate at which the ocean transports and stores this CO_2 determines how rapidly this radiatively active gas can be sequestered in the ocean reservoir by natural processes. During the mid-1980s, the ocean absorbed more than seven billion tons of carbon dioxide per year. This figure is steadily increasing with rising atmospheric forcing. The addition of anthropogenic carbon dioxide to our climate system is evident from the meridional cross-section through the Atlantic taken in 1991 and 1993 (Figure 2). Both the observations (upper panels) and ocean biogeochemistry models results (lower panels) show a strong southward penetration of the anthropogenic carbon dioxide from the northern North Atlantic where convection carries the signal from the surface to the ocean depths. Understanding the pathways for this signal at depth is critical if we are to decipher how the ocean buffers climate changes.

Scientists' ability to detect with certainty the presence or absence of an anthropogenic climate signal has been hampered by the complexity of natural climatic variability and the relatively short period of well-instrumented records of observational data. The modern climate record is only about a century long, of which only the last 50 years of data are of desirable quality and density. Within that short record, however, patterns of repeated, and apparently coupled, decadal variability in the ocean and atmosphere have been identified. These patterns are associated with significant changes in precipitation and surface temperatures and with significant changes in oceanic biology. The El Niño-Southern Oscillation (ENSO) is perhaps the best known example of a linked ocean-atmosphere process that is driven by internal variability, but the signature of others has emerged. The North Atlantic Oscillation is an atmospheric variability mode that

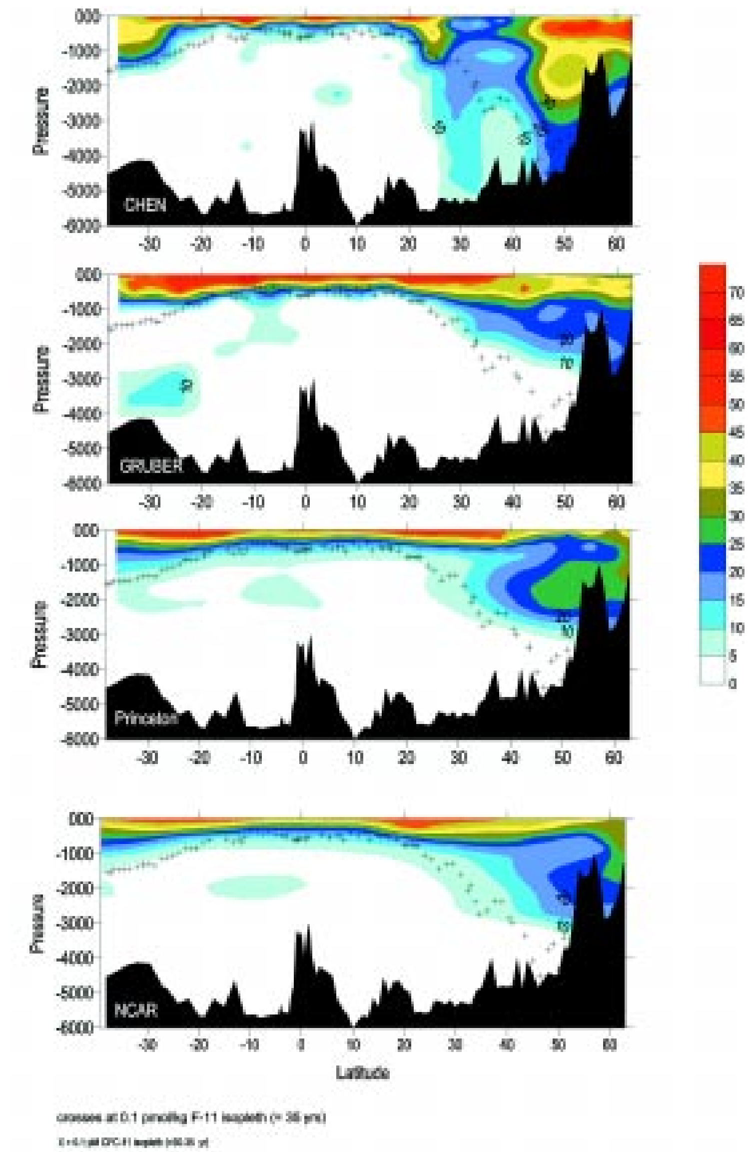


Figure 2. Estimates of anthropogenic carbon dioxide from the Atlantic basin along a meridional section in the center of the basin (nominally 20˚W). The fields in the top two panels were generated from observations taken from cruises in 1991 and 1993. The top panel used the methodology of Chen and Millero (1979) to generate the concentrations, while the second panel used the approach of Gruber et al (1996). The bottom two panels show the simulated anthropogenic carbon dioxide from the two different biogeochemistry models. Figure from: Wanninkhof, R., S. Doney, T.-H. Peng, J.L. Bullister, K. Lee, and R.A. Feely, Comparison of methods to determine the anthropogenic CO_2 invasion into the Atlantic Ocean, *Tellus-selected papers from the Fifth International Carbon Dioxide Conference*, **51B**, 511-530, 1999.

The Pacific Decadal Oscillation

Contributed by Nathan Mantua, University of Washington, Seattle

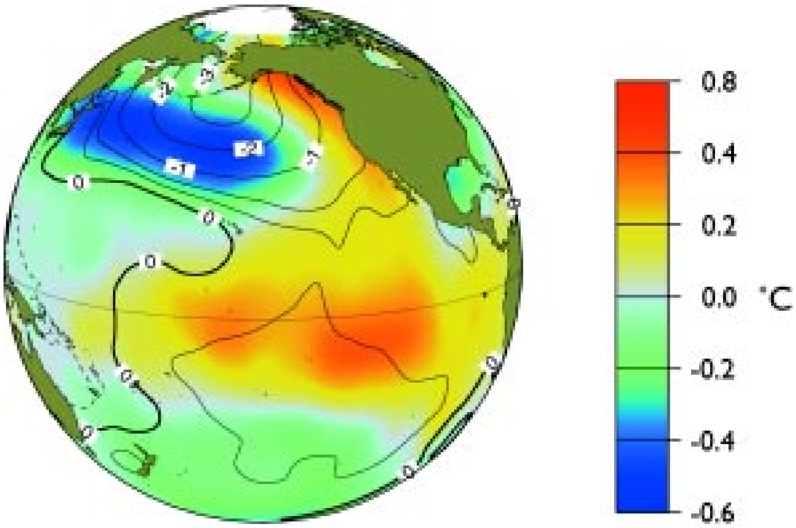
The Pacific Decadal Oscillation is a long-lived El Niño-like pattern of Pacific climate variability. The two oscillations have similar spatial climate fingerprints, but very different temporal behavior. Fisheries scientist Steven Hare coined the term PDO in 1996 while researching connections between Alaska salmon production cycles and Pacific climate.

During warm phases of PDO, ocean surface temperatures tend to be anomalously cool in the central North Pacific coincident with unusually warm temperatures along the west coast of the Americas. PDO sea level pressure anomalies vary in a wavelike pattern, with warm phases favoring unusually low pressures over the North Pacific and high pressures over western North America and the subtropical Pacific. These pressure patterns cause enhanced counterclockwise wind stress over the North Pacific and into northwestern North America. By construction, cool PDO climate anomalies are simply mirror images of warm phase anomalies.

The North American climate anomalies associated with PDO are broadly similar to those connected with El Niño and La Niña, though generally not as extreme. Warm phases of PDO are correlated with El Niño-like North American temperature and precipitation anomalies, while cool phases of PDO are correlated with La Niña-like climate patterns. PDO variability is strongly expressed in regional snow pack and stream flow anomalies, especially in western North America, and may also influence regional patterns of summer rainfall and drought in the US.

The most striking feature of the PDO is its preferred time scale of variability. While El Niño-Southern Oscillation (ENSO) events typically persist for 6 to 18 months, 20th century PDO eras have persisted for 20 to 30 years at a time. Several independent studies find evidence for just two full PDO cycles in the past century: "cool" PDO regimes prevailed from 1890 to 1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925 to 1946 and from 1977 through (at least) the mid-1990's (bottom figure). There is evidence that 20th century PDO fluctuations were most energetic in two broad spectral bands, one in periods from 15 to 25 years, and the other in periods from 50 to 70 years.

Important changes in Northeast Pacific marine ecosystems have been correlated with the PDO. For example, warm (cool) PDO phases have favored high (low) salmon production in Alaska and low (high) salmon production off the west coast of California, Oregon, and Washington states. These salmon production cycles are thought to arise from changes in the coastal ocean environment that alter the dynamics of the entire food web, including rates of phytoplankton and zooplankton production, species assemblages, and predator distributions.



Much controversy now exists over how PDO works, and how it might best be monitored, modeled and predicted. From a societal impacts perspective, recognition of PDO is important because it shows that "normal" climate conditions can change over time periods comparable to the length of a human's lifetime. The stakes in PDO science are high, as an improved PDO understanding offers even sharper views of the future than those now provided by ENSO science alone.

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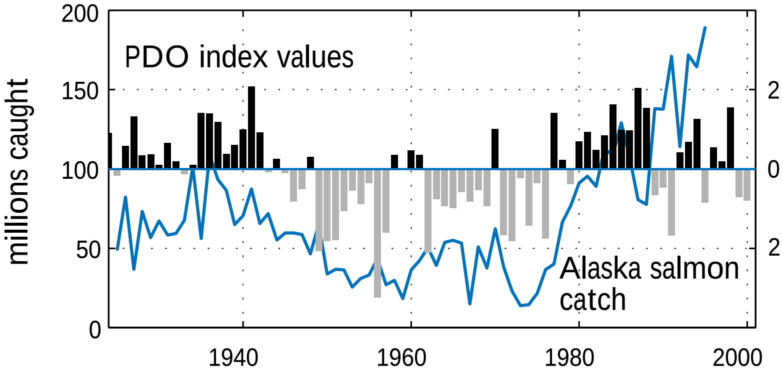


Top: A contour map showing gridded October-March averaged sea surface temperatures regressed on the normalized October-March PDO index. Solid (dashed) contours depict positive (negative) SST anomalies in °C.

Bottom: Time series of the normalized October-March PDO index (filled bars) and annual landings of central and western Alaska sockeye salmon, plus central and southeast Alaska pink salmon. These four Alaska salmon subgroups make up about 75% of Alaska's total annual salmon harvest.

is associated with significant changes in the ocean, including the rate of deep and intermediate water formation. A different pattern, the Pacific Decadal Oscillation, is observed in and over the Pacific (see PDO box on opposite page). Among other large-scale effects, this mode of variability is implicated in the rapid transition in seasonal climate statistics over much of the northern hemisphere during 1976-77. There is also an indication that there are interdecadal variations in the amount of sea-ice cover around Antarctica.

The internal oscillations discussed above create climate variability significant enough to complicate and/or mask climatic variability produced by greenhouse gas emissions. A major challenge to climate scientists today is to assess the degree to which these forcing mechanisms are controlling our modern climate and the degree to which man has affected the climate system. To meet this goal, we must study the variability of the natural (unperturbed by man) global climate, which can be gained by using proxy data from geological records.

Marine sediments extend our very limited historical and instrumental records into the realm of large-scale, natural climatic variability and reveal scenarios of extreme climate change that are comparable to those predicted for our immediate future. Marine sediments and their contained biologic remnants are multitrack recorders of climate and oceanographic change. Geochemical and biotic proxies have been developed to quantitatively estimate sea-surface temperature change, the fluctuating magnitude of global ice volume, changes in deep- and surface-water circulation patterns and heat transport, changes in continental aridity, changes in the intensity and circulation patterns of the atmosphere, and changes in the CO_2 content of the atmosphere. We can make use of the global extent of the marine sedimentary record to develop comprehensive pictures of past oceanographic conditions and to identify times when both the average state of the climate system and the boundary conditions of this system were substantially different. Oceanographic and climatic data obtained from the global array of marine sedimentary sections, when combined with the high time-resolution record of atmospheric composition found in cores from the Greenland and Antarctic ice caps, have begun to give us insight into the phasing of changes within the climate system.

WHAT ARE THE BIG PROBLEMS?

In light of the urgent need to distinguish between natural climate variability and anthropogenic interference with the climate system, it is imperative that we understand the interrelationships among carbon, heat and climate. The ocean is of central importance as scientists seek to determine what balance can be achieved between mankind's sources of carbon and nature's sinks. We need to understand the nature and extent of the ocean-induced delay in atmospheric warming created by rising CO_2 levels. And, we need to understand the sensitivities of the inherently turbulent, coupled atmosphere-ocean system to anthropogenic interference.

Specific challenges facing ocean scientists are:

What are the linkages and delay times between carbon and climate?

The goal set for the industrialized nations at the 1998 Kyoto meeting of the United Nations Framework Convention on Climate Change was to achieve a reduction in greenhouse gas emissions to about 5% less than 1990 levels by 2010. Because our economy, and thus our energy use, has been growing apace in the last decade, the United States will likely fall short of this target, perhaps by 20% or more. Yet this "Kyoto" goal, hard though it may be, is only a small start on the road to stabilization. Reasonable calculations of economic growth show that if it is desired to hold atmospheric CO_2 levels at double the pre-industrial concentration of about 560 ppm, then a deviation from our projected course by about 3.67 billion tons of CO_2 per year will be required by about 2025, and about 15 billion tons per year by about 2050. These are truly enormous quantities, and achieving this goal could mean costly and radical changes for society. If we can determine with more certainty the linkages and delay times between carbon and climate, we may be able to adopt a less radical course. The large-scale variability of surface ocean CO_2 distribution has been coarsely mapped. With the availability of new low-power and low-cost sensors, and the clear definition of surface wind fields, it is now possible to make rapid progress in constraining the surface fluxes of CO_2 with much more rigor.

A better understanding of anthropogenic, centennial and longer changes in climate requires understanding the processes governing transport by the slow, voluminous, deep-ocean currents that carry climate signals from the sites of strong air-sea interaction into the ocean's interior. While the movement of these deep currents is principally dictated by thermohaline circulation, it is at the sea surface that the ocean interacts with other elements of the climate system. Because surface ocean properties, which regulate ocean-atmosphere heat, freshwater and carbon dioxide fluxes, are imprinted by the fluctuating short-term climate anomalies, understanding long-term climate will require improved understanding of how the wind-driven circulation transports and mixes these properties.

In the ancient oceans it appears that atmospheric CO_2 may have played a pivotal role in the warm extremes of climates when concentrations reached three to four times present-day levels. We currently do not understand exactly how such high levels of CO_2 interacted with the oceans and the hydrologic cycle to produce a tropical climate not greatly different from today's, and a near-polar climate some 12°C warmer than today's. How these conditions developed, how they were maintained and how Earth's climate eventually returned to conditions closer to those of present day is one the most perplexing problems of paleoceanography and paleoclimatology. To address those problems we need a much clearer picture of what these ancient oceans were really like. What was their surface circulation like under conditions of weak pole-to-equator thermal gradients, and what was the vertical structure and mixing in ocean basins with a vertical temperature gradient that was half that of today's? To what degree did thermohaline circulation supply the heat needed at higher latitudes to keep the Arctic and Antarctic largely ice-free, or was an ice-free Arctic a prerequisite for a warmer climate? The Arctic sea ice in the modern world appears to be gradually thinning and decreasing in extent and may disappear in summertime altogether in 50 years with large consequences for the radiation balance at high northern latitudes. These puzzles from the past have immediate modern significance.

What is required to achieve the stabilization of greenhouse gas concentrations?

Each year the two-way exchange of CO_2 gas between air and sea is about 330 billion tons per year; the net flux of about 7-10 billion tons into the ocean from mankind's industrial activities is a small fraction of this. And, each year photosynthesis in the ocean fixes some 180 billion tons of CO_2, most of which is very quickly recycled. It is clear that small changes in these large numbers could have a powerful effect on our planet, and the basic scientific knowledge of what keeps these fluxes in check is an essential goal if we are to understand what is required to achieve stabilization of greenhouse gas concentrations. Ocean science can provide much of this critical knowledge by better constraining the surface fluxes of CO_2 (as noted above).

The linkage of biogeochemical cycles and the biological carbon pump with the overturning of water masses to form deep water is a classic problem that is critical to a better understanding of carbon cycling within the ocean. We are entering an era of new understanding of the statistics of this process. We now recognize early warning signs of processes that lead to the deep convection events which ventilate the oceanic depths.

A technological aid to achieving the stabilization of greenhouse gas concentrations may be required in addition to conservation efforts and the development of alternate energy sources. Because the oceans are the largest active reservoir of carbon in stored and dissolved form, they are often considered the appropriate repository for the excess that humans produce. Pilot experiments that either enhance the biological carbon pump or directly inject anthropogenic CO_2 into the deep ocean have already been successfully carried out. We should more fully explore these options and be open to the development of other such techniques of carbon sequestration.

What could create abrupt climate change?

Within the paleoceanographic records there is clear evidence of rapid regime shifts that can take place within a few decades and then persist for centuries. The origin of these shifts is uncertain but both changes of the thermohaline overturning circulation and of the tropical circulation have been suggested as mechanisms. Climate records from deep-sea cores show that the current deep-water formation pattern in the North Atlantic can change within an average human life span, and has done so in concert with great episodes of climate change in the past. Such past rapid shifts in climate are seen not only in the North Atlantic and in the proxy data for temperatures over Greenland, but also in the indicators of the degree of oxygenation of shallow intermediate waters in the North Pacific. Thus, these rapid climate shifts are at least hemispheric, and probably global, in extent (see Rapid Climate Change box on opposite page). Sophisticated climate models project that a rapid collapse of thermohaline circulation is possible as a result of the changed hydrologic regime from global warming, with fresh water stabilization of the upper layers. We need to determine the likelihood of such an event as a function of anthropogenic forcing.

In the more distant past, during a warm episode of climate, a very large and abrupt shift in climate has been well-documented. In this case the abrupt shift to an even warmer climate is believed to have resulted from a near-catastrophic destabilization of gas hydrates and release of large volumes of biogenic greenhouse gases that had accumulated in marine sediments (see Global Warming box on page 28). There are some indications that other such rapid releases of greenhouse gases may have induced abrupt climate changes at other times in the geologic past. Thus, there may be at least two (and possibly more) mechanisms by which abrupt climate change can occur–one driven by the hydrologic regime and one driven by atmospheric composition. Both seem to be linked to the oceanic part of the climate system and its passage through some critical threshold. The nature of these shifts in terms of their impact and the sequence of events leading up to them must be documented in the multi-proxy paleoceanographic records. With this independent evidence in hand we can more confidently evaluate climatic models that attempt to recreate such rapid climate shifts.

How can we predict climate variability?

Looking to the future, there are a number of ocean processes that must be better studied if we are to understand and predict climate variability and change. These include: (1) ENSO and other coupled ocean-atmosphere phenomena in the tropics that have an impact on global climate on interannual time scales, (2) patterns of slower decadal variability, of which the North Atlantic Oscillation and the Pacific Decadal Oscillation are the best known examples, (3) slower changes of the thermohaline circulation, (4) abrupt climate change and the interplay among atmospheric, surface ocean and deep ocean circulation involved in such changes, (5) the role of sea-ice cover and fresh water influx into the Arctic region on the climate-ocean circulation connection and (6) processes in the ocean, such as CO_2 sequestration, that affect possible anthropogenic climate change.

A prediction of our climatic evolution hinges on our understanding of the coupled ocean-atmosphere dynamical modes that are active in decade-to-century climate variability. El Niño-Southern Oscillation theory, observation and computer modeling provide a dramatic and important success story in ocean-atmosphere science (see ENSO box on page 40). The atmospheric tropical wind field responds to ocean surface temperature, and it also alters the ocean temperature through its control over mixing by wind, air-sea heat flux and upwelling. Yet the oceanic thermocline has its own dynamics involving long-wave propagations and transport by equatorial ocean currents. The two interact to produce an oscillation that is so clearly discernible in theory and models that it proves useful in climate predictions.

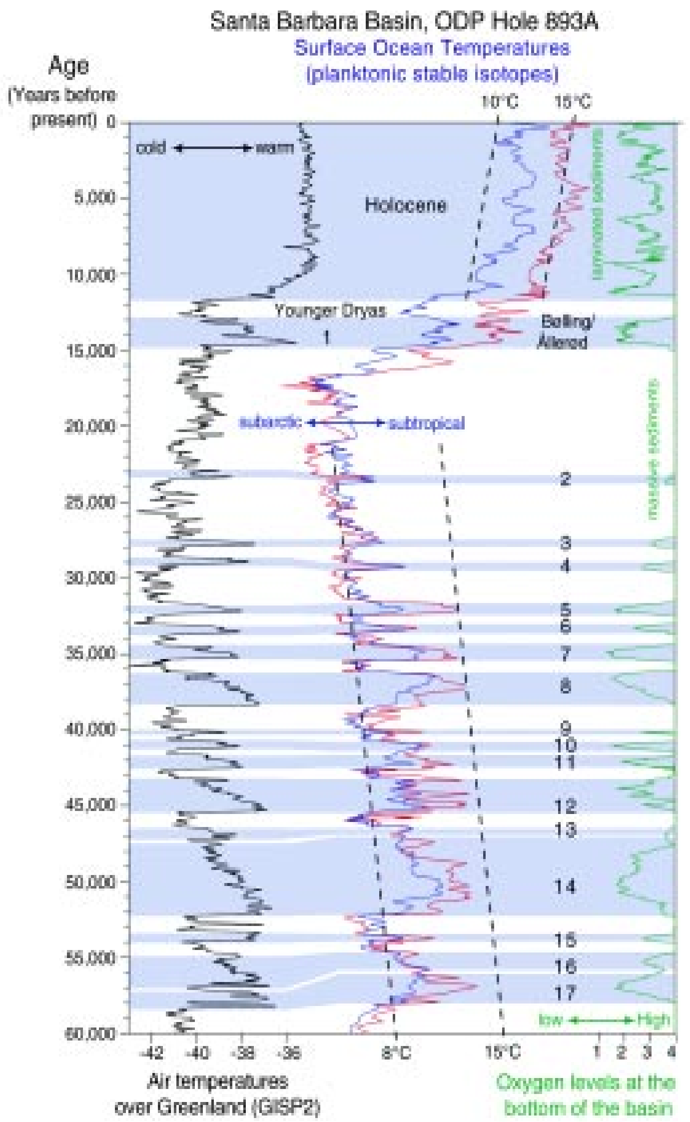
Outside of the tropics, climate variability is also strong and important in its impact on human activity. The nature of ocean-atmosphere coupling is more complex there, however. Over short time scales the atmosphere takes the initiative, for example, driving deep convection downwind of the continents where cold winds blow over warm ocean. The ocean has its own natural oscillations, particularly at very low frequency.

How Rapidly Can Climate Change?

Contributed by I. Hendy, J. Kennett and K. Cannariato, University of California, Santa Barbara
R.Behl, California State University, Long Beach

The surprising abruptness of climate change during the last glacial interval 10 to 60 Ka revealed in Greenland ice cores has forced scientists to rethink the climate change paradigm. A series of 17 warm climatic events (interstadials or Dansgaard-Oeschger events), each developing in fewer than 50 years and possibly in as few as three years, punctuated the cool climate during that time. These apparently global events lasted for 200 to 2000 years. Studies suggest that the Earth system response included changes in trade wind strength, Asian monsoons, air and sea surface temperatures, precipitation patterns and thermohaline circulation.

A combination of surface, thermoclinal and benthic proxy data from Santa Barbara Basin sediment cores provide insight into the workings of atmospheric, surface and intermediate water circulation during the Dansgaard-Oeschger events. These data also provide valuable information environmental and ecologic affects of ocean-climate change. Santa Barbara Basin is located at the confluence of the California and Davidson Currents, where surface water temperatures (SST) reflect the relative strength of both currents determined by broad North Pacific ocean-atmosphere interactions. During the last glacial interval, Santa Barbara Basin planktonic foraminiferal assemblages and isotope analyses demonstrate that regional surface circulation rapidly oscillated between strong and weak California Current flow, with varying strength in the subarctic and subtropical components in response to reorganization of the North Pacific atmospheric circulation. These SST oscillations can be tightly correlated to the interstadials recorded in the Greenland Ice Sheet suggesting an atmospheric connection between the two regions. This connection appears to have been basin wide, and may have affected the ventilation of North Pacific Intermediate Water (NPIW) as well. Currently, NPIW entering the basin is composed of low-oxygen, high salinity, warm water advected from equatorial regions, with a small component of well-ventilated, fresh, cool water from the subarctic North Pacific. Past changes in benthic foraminiferal assemblages and the activity of burrowing organisms at ODP Hole 893A demonstrate that the oxygen content of NPIW fluctuated synchronously with Greenland interstadials. Massive (bioturbated) sediments occurred during cool intervals of the last glacial, suggesting a proximal NPIW source, while laminated sediments of the warm intervals suggest a distal source and increased productivity.



Correlation between GISP2 δ^{18}O (SMOW) isotope time-series in black (Stuiver and Grootes, 2000) and planktonic foraminiferal and ventilation time-series for ODP Hole 893A for the last 60 Ka. δ^{18}O (PDB) records of thermocline-dwelling planktonic foraminifer *N. pachyderma* are in blue, and the surface-water planktonic foraminifer *G. bulloides* are in red (Hendy and Kennett, 2000). The 893A bioturbation index is in green (Behl and Kennett, 1996). Changes in all of these parameters clearly define the Dansgaard/Oeschger events (numbers 17-1) during the last glacial.

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Global Warming 55 Million Years Ago

Contributed by Richard Norris, Woods Hole Oceanographic Institution

About 55 million years ago, near the Paleocene-Eocene Boundary, deep-ocean, high-latitude and continental temperatures rose by 4° to 7° C, accompanied by mass turnovers of terrestrial and marine flora, fauna and microbiota. New data from deep-sea drilling cores suggest that the warming associated with this time interval—which has been termed the "Late Paleocene Thermal Maximum" or LPTM—was linked to the release of greenhouse gases to the ocean and atmosphere at rates approaching current anthropogenic inputs. The geochemical signature of LPTM greenhouse warming lasted for nearly 200,000 years, suggesting that our industry and lifestyle generate not only abundant CO_2 but will also have long-term biogeochemical consequences for our environment.

Marine and terrestrial records from the LPTM display a prominent negative carbon isotope excursion of at least 2.5‰, which is thought to record the massive input of greenhouse gas into Earth's atmosphere and oceans. A growing body of evidence suggests that the carbon's source was a small portion of the vast reservoirs of frozen methane hydrates buried in marine sediments. Recently drilled cores from the Southern Ocean and North Atlantic indicate that the massive release of methane occurred over an interval of ~50,000 years—not continuously, but in a series of three or four catastrophic events, each lasting less than a thousand years. One possibility is that submarine landslides allowed deeply buried gas deposits to vent directly into the ocean or atmosphere. After methane, or its decomposition product, CO_2, reached the atmosphere, greenhouse warming followed. The warming in turn heated bottom waters enough to melt more methane hydrate, trigger further releases of methane into the ocean, and perpetuate the cycle of global warming.

We know little about what started or reversed the cycle of greenhouse gas release and warming. The LPTM may have been triggered when two million years of gradual warming melted previously frozen gas hydrates, or as extensive volcanism in the North Atlantic altered ocean circulation or climate. As the LPTM continued, the cycle of gas release and global warming did not exhaust the reservoirs of methane hydrate, but biological production may have absorbed the "excess" CO_2 and effectively ended the LPTM. Alternatively, the cycle of greenhouse warming and gas release may have melted the top level of buried gas hydrate but left deeper deposits frozen and intact. The common thread among each of these possibilities is how gas hydrates may have profoundly influenced global climate by alternately storing and releasing greenhouse gases to the atmosphere and hydrosphere.

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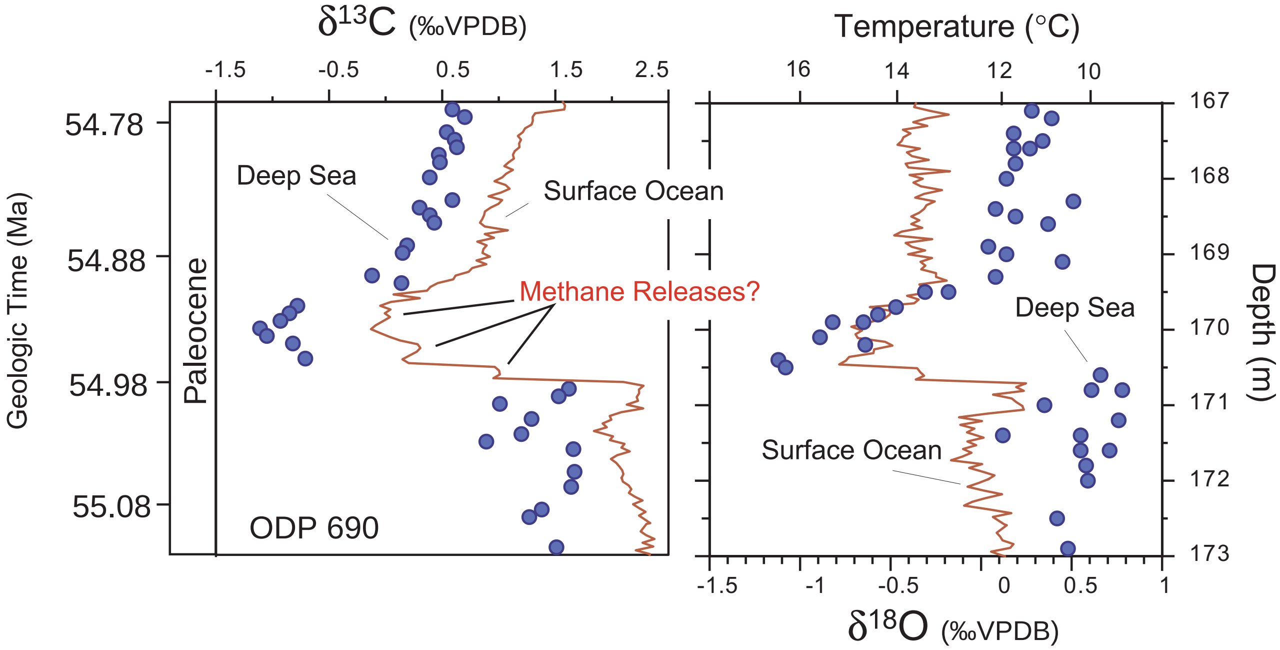

Abrupt changes in temperature (right) and carbon chemistry (left) at the Paleocene/Eocene boundary (~55 Ma). Global warming of surface and deep ocean by 3-7°C accompanied the massive release of greenhouse gasses from marine sediments and precipitate a major extinction in the deep ocean and changes in terrestrial floras and faunas. Global warming appears to have been ended by the uptake of excess CO_2 by plants on land and in the oceans. The Paleocene/Eocene event is a natural example of the climatological and biological effects of greenhouse gas emissions as a scale similar to the rates of anthropogenic releases of heat trapping gases today.

Feedback of sea-surface temperature fluctuations on the atmosphere is weaker and more subtle than the tropics. Computer models and simplified box models suggest that oscillations of the ocean can happen with a variety of periods, from a few decades to thousands of years. Such oscillating ocean circulations can be excited by the random excitation of the atmosphere, or they can develop two-way feedbacks that make them truly coupled modes. The Antarctic circumpolar wave is such a mode, with a period of about ten years. It apparently develops when changes in winds cause changes in north-south movement of the upper ocean thermal structure, which in turn feeds back, shifting the pattern of westerly winds.

The North Atlantic Oscillation (NAO) involves the tracks of storms in the northern Atlantic, and their intensity. It has a great impact on temperature and rainfall in the eastern US and Europe, and fisheries in the northern Atlantic (see Figure 5, page 41). In the 25 years after 1971, the strongly positive NAO has driven deep, cold convection in the northern Atlantic, which has affected the pattern of oceanic meridional overturning. The NAO operates over a vast range of time scales, from a few days to a century or longer. Its impact is significant in surprising places, for example, river flow and drought cycles in the Tigris-Euphrates river system in the Middle East, and the occurrence of cold-air outbreaks in the central US. The Pacific Decadal Oscillation (PDO) describes cycles with a period of 20 to 60 years (the duration of a cold or warm phase being one-half the period) and has a direct impact on salmon migration and US weather (see PDO box on page 22).

Despite the presence of modes of oscillation such as NAO and PDO in computer models, it is not yet known how much feedback is involved. Within the atmosphere, the tendency of Rossby waves to be deflected by NAO-related wind fields argues for an atmosphere-only oscillator, and passive response of the ocean. Yet, the broad range of periods observed in the NAO argues that the ocean may be active at the decade-to-century time scale. Interaction between the Arctic and Atlantic oceans is particularly apparent at decadal time scales. Whether or not coupled ocean/atmosphere dynamics is important to these climate modes, and whether or not they are forced by greenhouse gases, their strength and pattern structure provide new paradigms for global change. The strong oceanic activity within this domain argues for intense examination of their dynamics.

Efforts to extend into the future the detailed records of oscillations in the oceans and in Earth's climate system should go hand-in-hand with efforts to extend them into the past. In the past two decades the development of proxy records of past climate change with seasonal to annual resolution has shown that oscillations such as those associated with ENSO can be traced back hundreds and even thousands of years. This effort is still growing. It is not an easy task to tie the spectrum of climate variability in one place to that of another because there are marked regional differences in the response of the climate system to these oscillations. An important opportunity awaits us in the next decade to increase our fundamental understanding of the physical character of these oscillations, to obtain and develop proxy records of these oscillations, and to evaluate their long-term spectral character and stability. An increased fundamental understanding of these oscillations and their influence on global climate will be derived from defining their character through time and determining the spectral interplay between these oscillations under differing boundary conditions.

What are the pathways for climate signals in the ocean?

While the current sites of deep convection are largely known, a quantitative understanding of the pathways and rates of the warm-to-cold conversion of water is needed to assess the ocean's sensitivity to climate events. Thermohaline circulation's rate, volume and properties are all affected by the processes that control convection. Although in models it is salinity that causes the greatest changes in the thermohaline circulation, previous focus in understanding the thermohaline circulation has been on thermal forcing, rather than on freshwater, presumably because the source-sink distribution of heat is much better known. Although essential to understanding modulation of convection, knowledge of freshwater inputs from continents, precipitation and melting sea-ice is particularly lacking. Tracers, such as oxygen isotopes, can be invaluable in gaining this knowledge. Also necessary to understanding the hydrologic cycle is knowledge of how river runoff in the Arctic influences the surface waters of the Atlantic and Pacific, and ultimately the thermohaline circulation. To improve our understanding of the role of the hydrologic cycle in the climate, an improved knowledge of the rates, pathways, storage and redistribution of water in all its phases will be necessary.

This assessment will require better observations of the air-sea exchanges of heat and freshwater and it will require that all available ocean and meteorology data be integrated into global models. It will also require us to obtain and decipher paleoceanographic records from the highest latitudes of the northern and southern hemisphere such as the Arctic Ocean and the southern Weddell and Ross Seas.

The rates and pathways by which surface waters move from areas of air-sea interaction into the deep ocean and then back to the surface are also essential to understanding the ocean's role in climate. These processes involve most elements of the general circulation including meridional overturning, subduction, convection, western boundary currents (and their interaction with the interior through recirculation), and the diapycnal mixing that returns deep waters to the surface. These same processes control the geochemical recycling of nutrients that have a direct impact on the biologic productivity of the oceans and the very structure of the oceanic food web from its primary producers to the high-level predators. Traditional analyses based on temperature and salinity will continue to be important in diagnosing these processes, but geochemical tracers are particularly useful in providing estimates of water-mass age (see Tracer Release box on page 57) and in quantifying diapycnal mixing, while direct velocity observations are needed both in concentrated boundary currents and the ocean interior.

The Iron Fertilization Experiment

Contributed by Kenneth S. Johnson, Monterey Bay Aquarium Research Institute

Twenty percent of the ocean's surface waters are replete with the major plant nutrients such as nitrate, but few phytoplankton grow and the nutrients are not consumed. The lack of growth has important implications. Computer models suggest that phytoplankton growth in these High Nitrate, Low Chlorophyll (HNLC) areas could pull large amounts of carbon dioxide from the atmosphere and lower Earth's temperature. Plankton blooms in the HNLC areas may have been a major force driving Earth into glacial ages. Why do phytoplankton not grow in HNLC waters today?

It was suggested as early as the 1920s that HNLC waters were produced when iron, a trace nutrient required by all living organisms, limited plant growth. But, the concentrations of iron dissolved in the surface ocean are a few parts per quadrillion (a few parts per million of a part per million). Early oceanographers, working from iron ships with iron sampling wires and iron gear, invariably contaminated samples with iron. They could not show iron-limited growth because samples brought on board contained far more iron than occurred in the unperturbed environment.

The development of ultra-trace analytical capabilities pioneered by the ocean chemistry community clarified the HNLC water paradox. Measurements with these technologies demonstrated that iron was present in much lower concentrations than believed. Iron was particularly low in the HNLC areas, which receive little dust, a major iron source. Experiments with uncontaminated samples of seawater from HNLC areas showed that iron would, indeed, cause phytoplankton to grow in these waters, but it was unclear if these results could be extrapolated to whole ecosystems. Would zooplankton that avoided the sampling bottles simply graze phytoplankton stimulated by iron addition with no net change in biomass or nutrient consumption as a result?

The IronEx experiments were designed to test the hypothesis that iron addition would allow phytoplankton biomass to increase, consuming nitrate and carbon dioxide. A 10x10 km patch of ocean in the HNLC waters of the equatorial Pacific was fertilized with 400 kg of iron and marked with a few grams of the inert tracer sulfur hexafluoride on day 150 of 1995. Chlorophyll concentrations, a proxy for phytoplankton biomass, rapidly increased within the area marked by the sulfur hexafluoride tracer from initial concentrations of <0.2 mg/L to values >3.0 mg/L by day 158 (Figure). The biomass of phytoplankton increased by more than 2 million kg in the fertilized area, illustrating the tremendous impact of small amounts of iron.

The ecosystem response to the IronEx experiment has several important impacts on ocean sciences. First, it demonstrates conclusively that iron regulates biomass accumulation in the HNLC waters of the equatorial Pacific. Subsequent experiments have extended these conclusions to the Southern Ocean. Modest increases in the flux of dust borne iron to the ocean, as seen in Antarctic ice cores, would clearly have the potential to create large reductions in atmospheric carbon dioxide by stimulating phytoplankton growth. Iron and phytoplankton are probably closely tied to glacial cycles. Perhaps more importantly, the IronEx experiments show the potential for well-controlled experiments to be conducted on open-ocean ecosystems. Marine chemists and biologists could conduct controlled experiments designed to disentangle the complex interactions that control ecosystem structure and biogeochemical cycles in the ocean.

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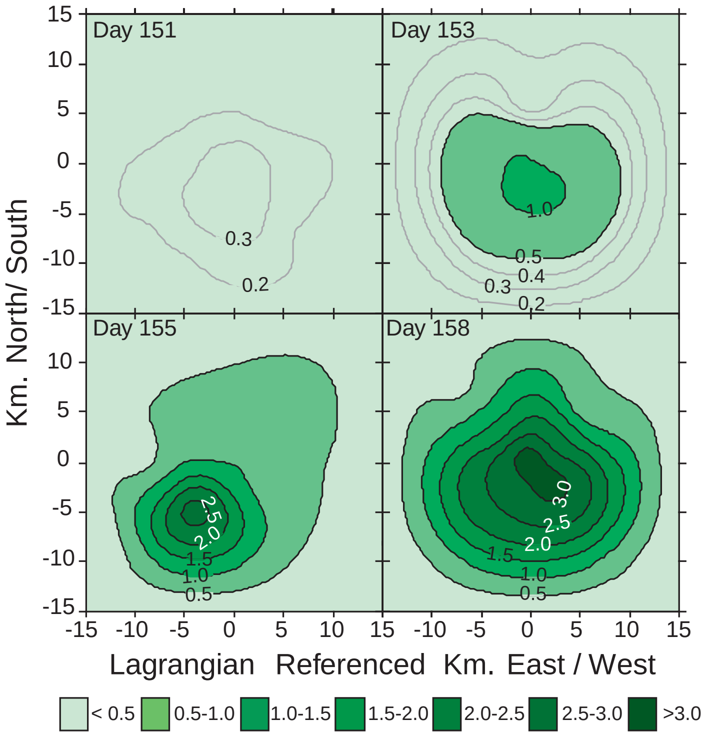


WHAT MAKES PROGRESS POSSIBLE NOW?

There have been major advances in the past few decades in our ability to observe the ocean and to delineate the processes that both control circulation and have an impact on global climate. We have been able to recover and decipher records of past climate states and to begin to evaluate the natural variability of the climate system. Our improved understanding of the present and past climate systems and enhanced computer technology have placed us on the threshold of new discovery. Some of the steps that have brought us to this threshold include:

- **A succession of successful field programs.** Measurements made primarily through the World Ocean Circulation Experiment (WOCE) have resulted in the recent compilation of global data sets of temperature, salinity, velocity and various tracers. Collectively, these data sets have given oceanographers an unprecedented view of the contemporary ocean circulation. The success of the Joint Global Ocean Flux Study (JGOFS) and WOCE programs in the 1990s has created the first two decadal time series of CO_2 in the oceans. The global survey of CO_2 in the oceans, carried out with unprecedented accuracy by scientists of many nations, has been completed and allows us to place calculations of the oceanic transport of heat and CO_2 on the same observational and theoretical basis.

- **Satellite observations.** Within the last decade polar orbiting satellites observing the ocean have become a reality, providing global coverage of critical properties every few days. The Topex-Poseidon radar altimetric mission provides sea surface height, from which changing ocean dynamics can be observed. The SeaWIFS sensor provides ocean color at several wavelengths. The successful launch of the NASA Terra satellite adds to this observing power. It is now possible to study in near real time the fluctuations of the great physical and biogeochemical controls on carbon dioxide around the globe. The use of these data is in its infancy, and we may expect rapid progress by linking satellite, ship and moored observations in truly innovative ways.

- **New observational and measurement technologies**. New measurement techniques have made possible direct observations of diapycnal mixing and basin-scale patterns of absolute velocity, monitoring of the tropical wind fields that drive the oceanic equatorial waves of ENSO, and significantly improved measurements and parameterizations of air-sea fluxes. These have already been used to improve theoretical understanding and numerical models of the ocean's role in climate.

  The rapid development of moored sensors for CO_2 and ocean biogeochemical properties has led to the possibility of time series observations at high latitudes, where climate change effects will be critical. Similarly, the development of sensors carried on autonomous vehicles allow exploration under the ice, and the survey of deep water convection events in progress. The increasing sophistication of drifters and floats have allowed for a novel view of ocean circulation by providing Lagrangian pathways.

The measurement of ^{14}C, the essential radiochemical clock for deep-sea circulation studies, has been revolutionized by accelerator-mass spectrometry. Measurements that earlier required 200 liters of seawater can be made with just 1 liter, in shorter time and at lower cost. Combined with increasingly sophisticated chemical separation methods, ^{14}C ages are being derived from small amounts of specific organic compounds, increasing the confidence in this dating method.

Paleoceanographers have devised multiple, independent ways of estimating past temperatures in the oceans, circulation pathways of deep ocean waters, and paleo-productivity. They can trace the weathering of the terrestrial parts of the planet and the delivery of sediments to the oceans via both rivers and winds. They are even approaching the very difficult problems of estimating paleo-salinity, pH of ocean waters, and CO_2 content of the atmosphere in the distant past.

- **Successful pilot experiments**. A whole new set of bold, innovative and important pilot experiments, which have now been successfully completed, pave the way for rapid advances. Among these are studies of the deep Brazil basin (see Tracer Release box on page 57) and the Greenland Sea where the injection of sulfur hexafluoride (SF6) is used to trace circulation and mixing. Pilot experiments seeding the ocean with iron resulted in the rapid development of a phytoplankton bloom, strongly drawing down CO_2 levels (see Iron Fertilization box on page 31). By adding SF6 tracer along with iron, the movements of the fertilized patch could be traced, and the effects of mixing accounted for. Sequestration of CO_2 in the deep ocean could potentially reduce or eliminate the atmospheric residence time, and the climate forcing that accompanies it. The first small scale pilot studies to explore this process have now been carried out.
- **Enhanced predictive capabilities.** The Tropical Oceans and Global Atmosphere (TOGA) program has established both the basic dynamics of ENSO, involving wavelike motions in the oceanic equatorial waveguide and air-sea latent heat transfer that drive atmospheric convection, and has led to seasonal predictions with useful skill.
- **Innovations in modeling and data assimilation**. Until quite recently the problems of useful simulations of ocean physics and climate were so hard that applications to the carbon cycle were set to one side. It is now common to carry a full set of CO_2 system variables in climate models, and to incorporate not just the "tracer" fossil fuel CO_2 signal, but the full range of ocean biogeochemical cycles. This has lead to useful predictions of change, which will be tested by innovative experiments.

WHAT IS REQUIRED FOR PROGRESS?

To provide the essential information that society needs to make wise choices for its future, we need to create a coherent ocean climate program. Such a program should advance our understanding of physical oceanography, paleoceanography and the ocean carbon cycle.

- **Continued observation and understanding of the ocean.** The knowledge of climate that we have today is based upon a background of continuing ocean observations, satellite data streams, assimilation schemes and numerical models. It is essential that these continue. Without this network, prospects for more detailed understanding can not be assured.
- **Extend the time-series stations.** As part of an effort to unravel our evolving climate, we should create the next generation of observing programs. Because we cannot observe all the ocean at all times, critical choices must be made. The only two existing time series stations at Bermuda and Hawaii (see HOTS box on page 50) provide essential data, and must be maintained. But the extension of time series capability to a significant number of climate critical locations, such as the far North Atlantic, is needed in order to capture the early signals of climate change. This will require the innovative extension of mooring and sensor technology.
- **Support satellite and ship-based observations.** The full impact of near real-time satellite observations on experimental planning has yet to be felt, yet the intelligent folding of these two observational modes has the potential to revolutionize carbon and climate studies. In particular, the ability to capture deep-water formation events as they unfold is critical. The development of modern autonomous underwater vehicles, which can adapt to events, has provided an important new dimension to the efficient solution of these problems.
- **Enhance ocean modeling, data assimilation and theory.** Large-scale numerical models of the ocean are the essential tools for casting the results of theory and observations into rigorous form. A period of fertile interaction of experiment, theory, data and modeling is needed in order to make significant progress in our understanding of the climate system. For example, the real ocean contains energetic, small-scale eddy features that can not be explicitly resolved in models, however, these features often dominate the scale of observations made from ships. Ocean experiments can rarely obtain volume closure, and questions on the boundary conditions continue to plague numerical simulations.

- **Obtain high-resolution records of past climates.** Certain areas of high sediment-accumulation rate contain detailed records of climate that can provide information on oceanographic conditions such as temperature, salinity and biologic productivity in a wide array of geographic locations. Similarly, coral growth bands and growth bands of long-lived mollusks provide oceanographic records with seasonal to annual resolution. These records can extend our understanding of natural oscillations in the ocean system back thousands of years. Although they may not provide as detailed a view of the world ocean as a global ocean observing system might give us in the future, the records of the past already exist and await our efforts to gather and interpret them. To obtain long, high-resolution sediment records there is a basic need for a long piston-coring capability. In some areas where sections are very thick and thus have very high time resolution, access to dynamically positioned, deep-water drillships and mission-specific drilling platforms will be required.
- **Obtain records of extreme climates of the past.** Our knowledge of Earth's climate system during extreme warm times is inadequate; the availability of samples is sufficient only to tell us that such conditions existed. Samples indicate an ice-free Arctic and Antarctic, and thermal gradients in the ocean which were generally half that of modern times. The exact nature of tropical climates during such warm times, however, is a matter of debate. The impact of such a diminished gradient on wind-driven circulation has yet to be documented, and the nature of thermohaline circulation has not been firmly established. Thus, we are uncertain as to the mechanisms that maintain heat transport from low to high latitudes in such warm times or that diminish radiative losses in high latitudes. We know little of the vertical stability of the ocean in such warm times or the effect that the potential changes in the stability structure of the upper ocean might have on ecosystems. The need for drilling platforms is particularly acute for sampling older parts of the geologic records when these extreme warm climates existed.
- **Develop new paleoceanographic proxies.** Over the past few decades we have learned that a multiple-proxy approach to describing paleoceanographic and paleoclimatic conditions is essential to extracting a reliable record of past climates. We also need geochemical and biotic proxies for as many climatic and oceanographic variables as possible. The more completely we can describe past conditions the more certain we are of our interpretations. For example, recently developed approaches to evaluating past CO_2 concentrations of the atmosphere show great promise in linking atmospheric and oceanic environments of the past. We must continue to develop innovative approaches to the quantitative estimation of past climatic and oceanographic conditions. These proxies are often expressed as variations in elemental, isotopic or molecular composition in various organic and inorganic phases. Hence, progress may well be dependent on a better understanding of the basic physiological and chemical processes that create and preserve these phases.

- **Develop and employ "whole system" climate models that are capable of predicting long-term (centennial scale) climate change.** Anthropogenic effects are, in present-day models at least, capable of producing changes comparable in magnitude and rapidity to those seen in paleoceanographic records. Study of response to anthropogenic forcing and of the dynamics of natural climate changes on centennial time scales is needed for scientific and national security reasons. These studies will differ from work on shorter time-scale variability in two substantial ways. First, the phenomena involve the full water column, whereas interannual and decadal variability are largely upper ocean phenomena. Second, we cannot rely on future observations to verify our methods of prediction because we cannot afford to wait that long. Thus in order to be useful, understanding in this area must be incorporated into models and those models must be tested thoroughly. There are two distinct approaches to such testing: (1) apply the models to the prediction of similar, but more rapidly evolving, phenomena, and (2) apply the models to oceanographic conditions of the past. Such hindcasting makes use of the paleoceanographic records that exist in the deep sea and can be recovered by ocean drilling and coring.

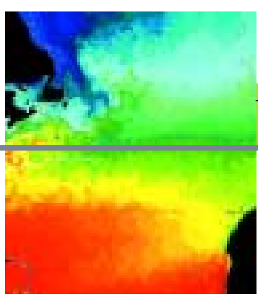
- **Extend the perturbation experiments.** The successful execution of tracer, iron-enrichment and CO_2-injection experiments has been a great stimulus to the ocean sciences. Important new results on the rate of ocean mixing, on fundamental controls on biogeochemical cycles, and on the realities of plans for carbon sequestration have rapidly emerged from these efforts. The adoption of these techniques, and the development of new classes of perturbation experiments has the potential to radically change our science.

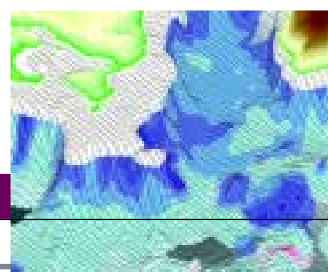
- **Assess the sequestration option.** The topic of carbon sequestration, either through iron fertilization or direct disposal, is perhaps the most controversial in all of the challenges facing ocean scientists and society. To put it bluntly, we know far too little to make any useful scientific judgement at this time, yet answers may be required quite soon. Apart from cost and engineering concerns, the basic chemistry, physics and biology associated with large-scale iron fertilization or releases of CO_2 in the deep sea are not well-known. While we can make sophisticated calculations of the fate of plant cells, of the dissolution of deep-sea calcium carbonate, of the circulation paths of a tracer, of the physical chemistry of hydrate formation or the effects of impurities in the injected material, and even the effects of low pH-high pCO_2 on marine animals, putting all of the effects into the context of carbon sequestration is a huge challenge.

LONG-TERM OCEAN OBSERVATIONS AND PREDICTION

The 1.2 billion cubic kilometers of ocean on Earth encompass resources, ecosystems and a massive piece of the dynamical climate system. To understand and predict the changing ocean, there is great need to capture in detail its baseline physical, biological, chemical and geological properties. The strict oceanic analog of weather forecasting would be to predict the amplification and decay of oceanic mesoscale eddies, tides and wind-waves. While these events are relevant because of their impact on marine resource management and ship movement, ocean prediction spans a much wider range, from climate changes involving the global ocean circulation to the adjustment of a marine ecosystem following the introduction of an exotic species.

Looking from the fantail of a research ship across a vast expanse of sea surface, we sense how small are our efforts to observe and understand the volume of ocean that lies below. Until the 1970s just a handful of oceanographers were traversing this domain. From underpowered, slow ships they lowered thermometers, plankton nets and water sampling bottles. While oceanographers now number in the thousands, and modern observational tools greatly extend our grasp, oceanography remains a "young" science because of the ocean's vastness.





New observational platforms and sensors, and faster computers, are needed to approach the problem. In the 1990s it took all the resources of the international community of oceanographers most of a decade to make one "snapshot" of the hydrography (temperature, salinity, chemical tracers), based on classical long, ship-based sections with typically 100 kilometer spacing between stations. The map of ship-tracks from this World Ocean Circulation Experiment shows just a few lines crossing each of the major oceans (and none in the Arctic). In the past decade many new technologies have converged, and finally we have the tools to map the oceans in three dimensions and the models to predict its future.

WHAT ARE THE BIG PROBLEMS?

Because of the physical scale and the complexity of connections and feedbacks, meaningful observations and predictions can be difficult to obtain. Examination of a few of the big problems, and in particular ones important to society, documents the progress that is being made but also highlights the difficulties remaining.

Ocean-Mediated Climate Fluctuations

The ocean is a great heat reservoir, energizing the atmosphere on many space- and time-scales. Atmosphere-ocean coupling is very complex, and despite rapid progress, observations are still too sparse and infrequent to constrain computer models of major parts of the climate system. The strongest currents in the ocean occur with horizontal scale of typically 100 km, far smaller than the width of major oceans (Figures 3 (a computer model) and 4 (ocean observations)). The smallness of these energetic eddies and jet-like boundary currents presents a major challenge to both observation and computer simulation.

Coupling between the atmosphere and ocean can involve active two-way feedback, as in tropical Pacific El Niño-Southern Oscillation (ENSO) cycles. Hurricanes and tropical cyclones are also intensely interactive air-sea events. Outside of the tropics the ocean still supplies heat energy to the atmosphere but the nature of coupled atmosphere-ocean interactions is not yet understood. At long time scales of a few decades or more, global numerical models indicate fully coupled climate cycles can occur, while at shorter time scales the atmosphere seems less sensitive to perturbations in the ocean. The relatively coarse spatial resolution of current numerical models may inhibit such interactions.

ENSO has taken ocean prediction to a new level of effort, sophistication and success (see ENSO box on page 40). The TAO array is the largest ocean mooring system ever deployed, spanning one quarter of Earth's circumference in the Pacific. The phenomenon itself is a dramatic example of coordinated atmosphere-ocean interaction. Theoretical calculations and coupled computer models have played important roles in discovering the chain of events that cause ENSO cycles. El Niño has a global effect on rainfall, temperature, storminess, hurricane frequency and subsequent effects on ecosystems and human diseases.

The NAO (North Atlantic Oscillation), which controls intensity and pathways of storms over the North Atlantic, has hit 100-year extremes during the 1990s; since 1972 it has been dominated by its positive phase with an intense Icelandic Low, yet with a dramatic reversal in 1996-97 (Figure 5). NAO controls winter weather in Europe, to a lesser extent in the northeastern US, and modulates deep-ocean convection as well as the exchange of Atlantic water with the Arctic. It has a strong effect on drought cycles in the Middle East (with the Tigris-Euphrates region experiencing a major drought during the recent 25-year, positive NAO phase). Global warming may also be expressed through enhanced NAO activity, and intensification of ENSO cycles.

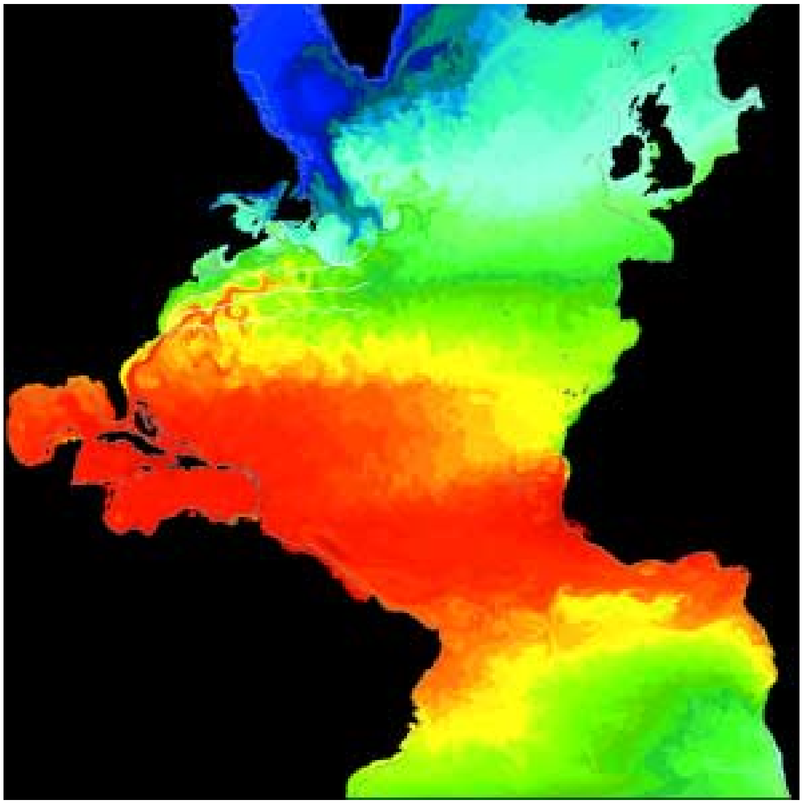


Figure 3. Temperature at the sea surface as modeled by a high-resolution (1/12⁰ grid), layered model of the Atlantic circulation. Eddies with diameters of about 100 km dominate the kinetic energy, along with the warm (red) Gulf Stream and the cold (blue) jet-like circulations of the subpolar ocean. It is this rich texture of dynamics that makes ocean prediction challenging. Figure courtesy of R. Bleck, MICOM project. http://panoramix.rsmas.miami.edu/micom/

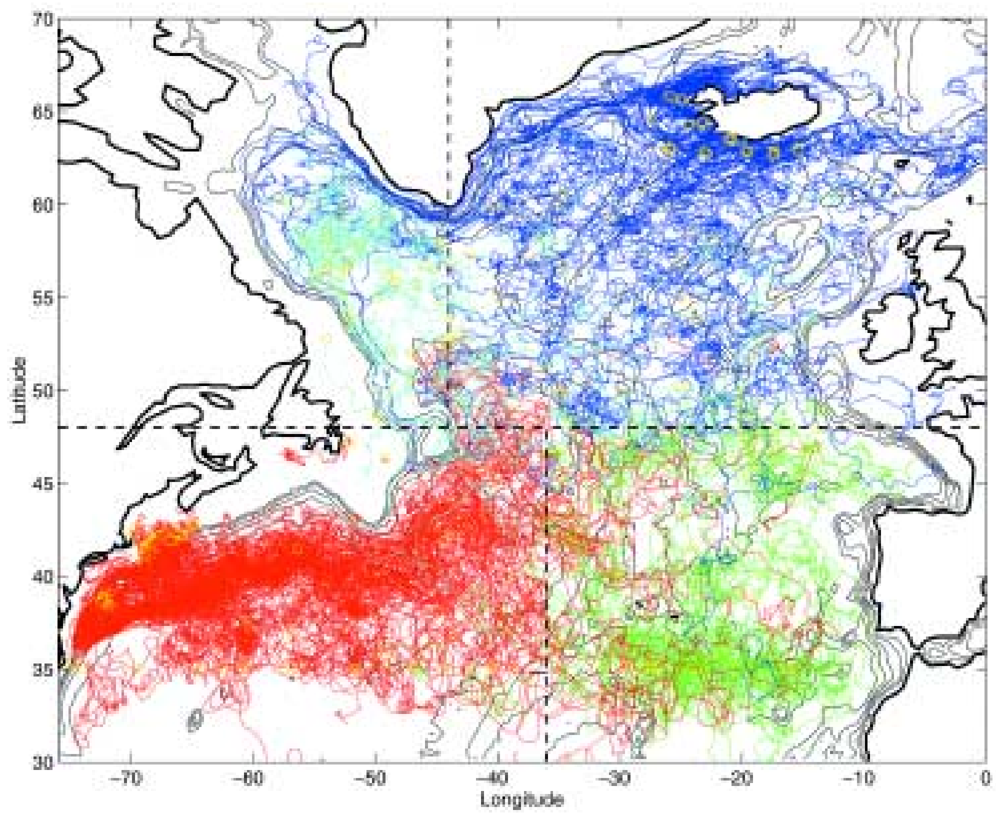


Figure 4. Tracks of drifting buoys (‘drifters’) on the sea surface, launched during 1996-1999 by Dr. P.P. Niiler. These give another view of the complex ‘fabric’ of the oceans. Tracks are colored corresponding to the ‘box’ (dashed lines) they were launched in. The tracks show intense eddy activity, superimposed on the general circulation. Typical duration of a track is 200 days; the gradual bleeding of colors from one box to the next is the way we visualize the ocean circulation.

Predicting the El Niño Southern Oscillation

Contributed by Mark Cane, Lamont-Doherty Earth Observatory of Columbia University

With the 1997-98 event, "El Niño" became a household name. Yet, as recently as late 1982 even many knowledgeable observers were unaware that the largest El Niño in several hundred years was already well underway. In 1985 the international TOGA (Tropical Ocean Global Atmosphere) Programme was launched with the goal of predicting the ENSO (El Niño and the Southern Oscillation) cycle—if possible. To an unexpected degree that goal has been met: ENSO events are now predicted well in advance with useful (albeit less than perfect) skill.

Our present understanding of ENSO identifies the tropical Pacific as the genesis region, and ocean-atmosphere interactions in that region as the generating mechanism. A now widely accepted theory treats ENSO as an internal mode of oscillation of the coupled atmosphere-ocean system, perpetuated by a continuous imbalance between the tightly coupled surface winds and temperatures on the one hand, and the more sluggish subsurface heat reservoir on the other. According to this theory, the memory of the coupled system resides in the subsurface ocean thermal structure. The crucial set of information for El Niño prediction is the spatial variation of the depth of the thermocline in the tropical Pacific Ocean. In 1985, when a physical model (the intermediate Zebiak-Cane model) was first used to predict El Niño (Cane et al. 1986), direct observations of oceanic variables were sorely lacking. The currents, thermocline depths, and temperatures that served as initial conditions for forecasts had to be generated by forcing the ocean component of the model with surface wind fields derived from merchant ship observations.

Though the observing system was certainly inadequate in the past, part of the legacy of the TOGA program is the TOGA TAO array of highly instrumented buoys in the equatorial Pacific. Since the mid-1990s, comprehensive physical models of the atmosphere and ocean have been increasingly used for ENSO forecasting (see figure). These more realistic models are better able to take advantage of the expanded observational network. In addition to subsurface temperature data and surface observations (temperature, salinity, sea level pressure) from the TAO moorings, most of these models routinely make use of XBT data from and between ships, fields of sea surface temperature derived from a combination of satellite and *in situ* measurements, including many from drifting buoys. On a still experimental basis they are incorporating satellite observations of sea level (Topex-Poseidon) and winds (NSCAT).

Though the common reaction to the first ENSO forecasts was surprise that it could be done at all, the question now is, why it isn't being done better? Forecasts of the 1997 event were generally regarded as successful, but few, if any, of the forecasts made before the event became evident in early 1997 predicted the outsized nature of what was to come (Barnstone et al, 1999). Even more than the inherently limited predictability of the chaotic climate system, present skill is limited by shortcomings in the models and the immaturity of data assimilation methodologies. As these improve, enhancements of the observing system must keep pace. The TOGA program created a prototype ocean observing system, leaving us with the simpler, but critical, task of maintaining and improving it.

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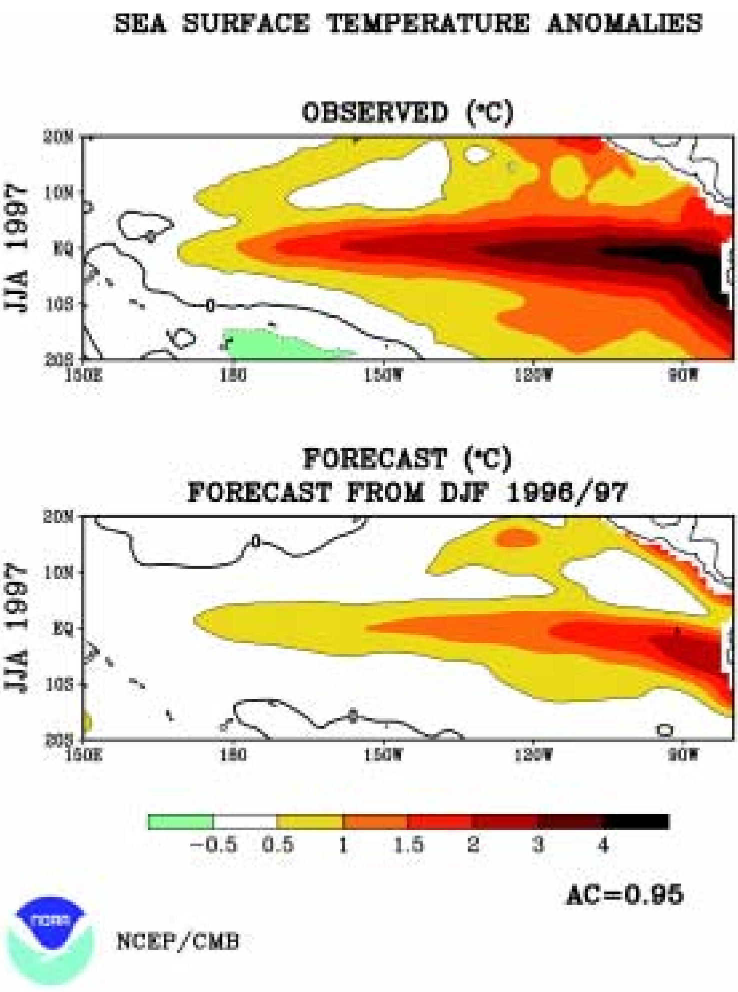
For more information on ENSO prediction, see http://iri.ldeo.columbia.edu.



Sea surface temperature anomalies in June, July and August 1987. Observed (top). NCEP forecasts from December 1996, January and February 1997 (bottom). Figure courtesy of Ming Ji, NCEP/NOAA.

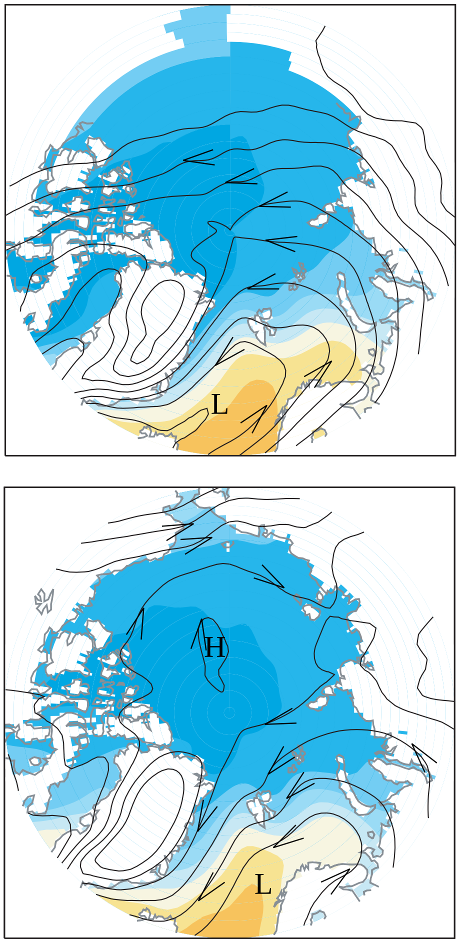
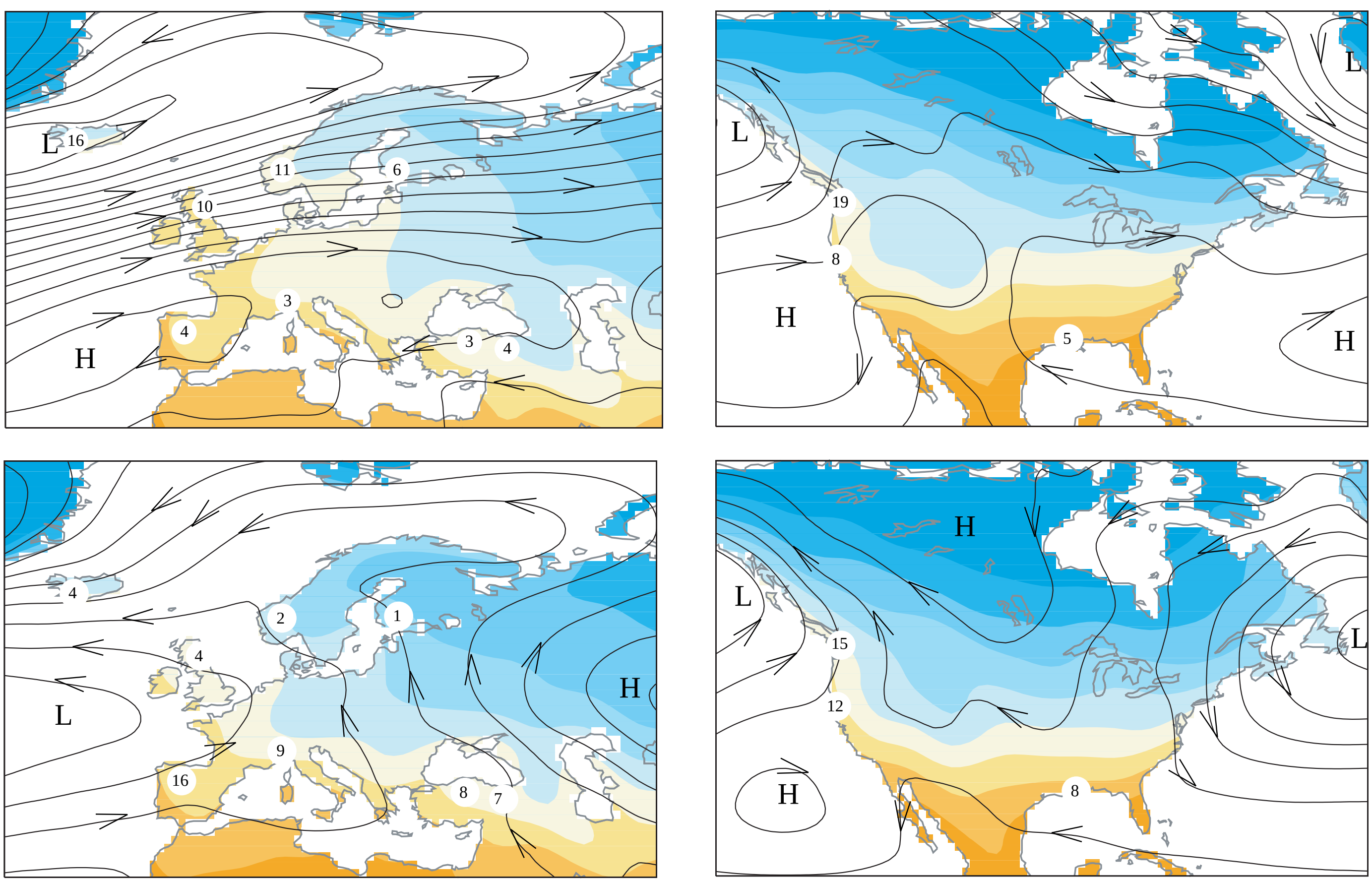


Figure 5. The North Atlantic Oscillation (NAO, and its close relative, the Arctic Oscillation or AO) affect winds, rainfall and temperatures over much of the northern hemisphere, but particularly the regions bounding the Atlantic Ocean. In this figure, the Arctic, European and US regions are shown at extremes of the AO (upper panels are positive extremes, and lower panels negative extremes). The wintertime (January-March) sea-level pressure (solid curves), surface air temperature (colors) and precipitation (numbers, cm/month) show the effect strong, high-latitude storms and jetstream during the positive phase (above). This phase had a long period of dominance between 1972 and 1995, bringing with it warmth and rain to western Europe, cold to eastern Canada and the Labrador Sea, and increased oceanic flow connecting Arctic and Atlantic. During the negative phase winter storms track farther south, off the US coast while northern Europe is colder and drier. Atmosphere-ocean interaction in the NAO is subtle and incompletely understood. Figure courtesy of David Thompson, Colorado State University.



The NAO (as measured by the Iceland-Lisbon sea-level pressure difference) has a broad frequency spectrum with extreme behavior in the last quarter century. Its predictability purely through time series analysis is not great, but increasing understanding of its dynamics should increase predictive skill. Among the important linkages are the remarkably "tall" atmospheric structure of the NAO, which reaches the stratosphere as a nearly polar-symmetric vortex, and signs of significant response of the atmosphere to the high-latitude SST perturbations. Paleoclimate time series (tree rings and potentially Greenland ice cores) may provide a much longer record of the NAO against which to measure predictive variance.

Studies with coupled ocean-atmosphere models suggest that components of the deep ocean circulation have predictability ranging beyond a decade. Indeed, some branches of the system are well-anchored, and prediction of, say, the spreading of Labrador Sea Water down the deep western boundary current of the Atlantic, following an intense year of deep convection, is becoming rather straightforward.

Variability of the Meridional Overturning Circulation

The ocean is organized in stable density layers that resist upward or downward flow. This stratification is perhaps the oceanic property of most importance to life on Earth, for it limits the upwelling of nutrient-rich deep waters to the sunlit upper layers. There are several key aspects of density-driven circulation that are inadequately understood and difficult to model: (1) Where are the main areas of deep-water return and what controls the rate of return? (2) How do we appropriately model a system that may have highly variable seasonal pulses of supply and yet may take hundreds of years to complete a circuit of circulation and (3) How are the present apparent changes in climate affecting this crucial system?

The ocean circulates in nearly horizontal gyres and jets, partially driven by winds, and in "up-down and north-south" concentrated arteries juxtaposed with much broader drifts of global scale. Sinking regions are few, yet where does the water rise? There is a tendency for fluids heated and cooled from above to rise broadly while

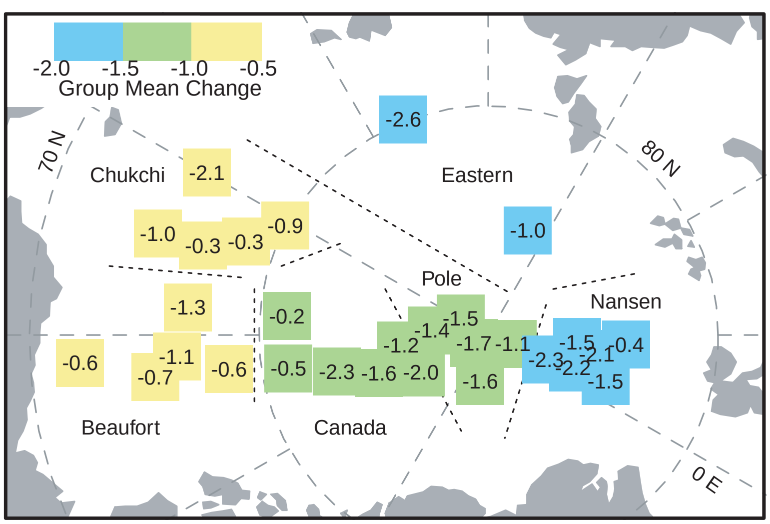


Figure 6. Changes in mean sea-ice thickness between 1958-1976 and 1993-1997 (meters). The mean thinning of the Arctic ice is about 40%. While not unequivocally a result of greenhouse-gas induced global warming, it is a striking change in Arctic climate. Figure is from Rothrock, D.A., Y. Yu and G.A. Maykut, Thinning of Arctic sea-ice cover, *Geophys. Res. Lett.*, **26**, 3469-3472, 1999.

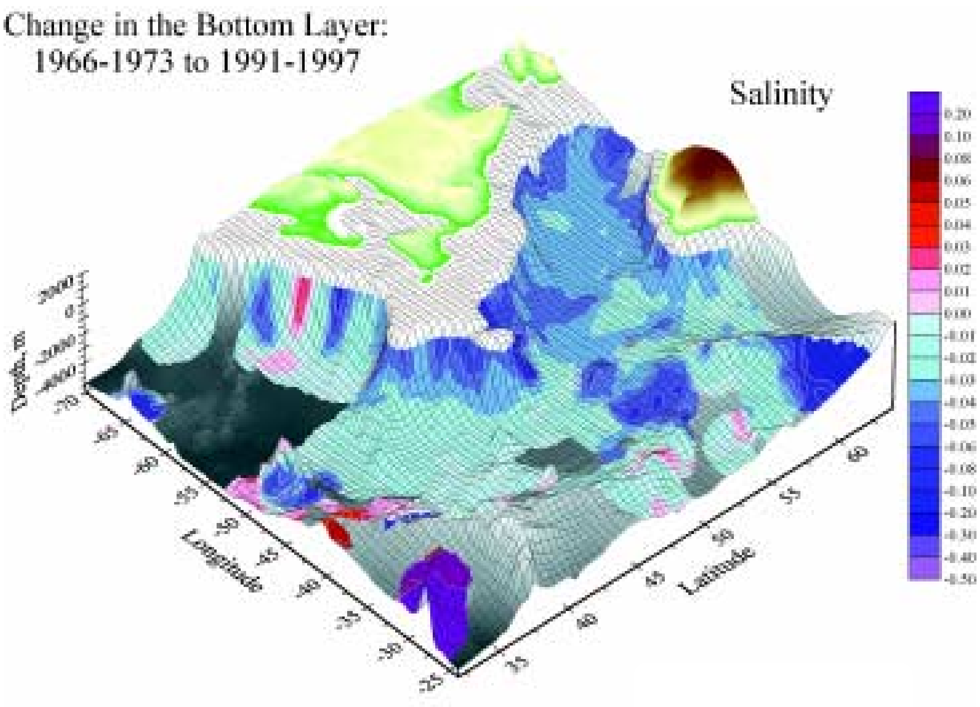


Figure 7. Change in salinity at the bottom of the northern Atlantic, between the 1960s and 1990s. Greenland is the 'ice mountain' along the upper right. Newfoundland and Nova Scotia lie at the upper left. This massive reduction in salinity is occurring in the most climatically sensitive place in the world ocean, and may be connected to the North Atlantic Oscillation, and to global warming. The few long-term records we have are invaluable to the understanding of decade-to-century changes in global climate. Figure courtesy of I. Yashayaev, Bedford Institute of Oceanography.

sinking in concentrated spots. The geographical distribution of turbulent mixing in the deep ocean in part controls this rising pattern, and new discovery of intense mixing over rough bottom topography, mediated by internal waves and tides, may signal the pattern of upward motion (see Ocean Turbulence chapter).

The slowness and tortuously long pathways of the meridional overturning present the second major challenge to computer models (the first being the small length-scale of important, energetic currents). It takes several thousand years for surface waters to sink, ventilate the world's ocean, and return to the surface. Computer simulations this extensive can be carried out only at the expense of spatial resolution. The very physics that controls the small regions of sinking and crucial regions of interior turbulent mixing is then poorly represented.

There is a multiplicity of possible circulations under the same atmospheric forcing, including situations known as "polar halocline catastrophes," in which a cap of buoyant water seals off the sinking regions from atmospheric cooling. Global warming is already beginning to increase the load of fresh water entering the ocean at high latitudes, both from polar melting (as possibly indicated in Figure 6) and from an accelerated hydrologic cycle—the warmer ocean evaporates more water into the atmosphere, which must precipitate somewhere. Observations in the Labrador Sea and Arctic show, over the past 25 years, an increasing load of low salinity water and exchange of water between Arctic and Atlantic (Figure 7). The buoyancy and increasing temperature of this fresh water suggest the possible slowing of the meridional overturning circulation. Coupled numerical models, though only beginning to incorporate high-latitude ice and convection, provide scenarios in which slowdown or shutdown of convective turnover could occur. The global impact of a major decline in oceanic heat transport could be very significant.

Rapidly Changing Coastal Environments

Many key physical and biogeochemical processes in estuarine, coastal and shallow sea environments occur on short time scales and at small spatial scales. For example, brief spells of low oxygen in an estuary can stress marine life; a pulse of nutrient-rich water upwelling from the deep ocean can trigger the onset of blooms and related species successions. Major dislocations of the coastal environment are occurring through a combination of human activity and climate change. These regions are both vulnerable and dense with human activity. Extreme impact on human populations can occur; in Bangladesh, for example, tropical cyclones and monsoonal flooding cause enormous loss of life and infrastructure, while promoting the outbreak of cholera. Recent advances in computational capabilities, combined with increasingly sophisticated observational technologies (e.g., remote sensing, telemetry, networking, autonomous underwater vehicles, the establishment of long-term monitoring systems) present unprecedented opportunity to advance understanding of shelf and estuarine systems and their management. Prediction of when and where key events will occur will enable targeted observations, and at the same time will allow decision-makers to develop strategies to restrict anthropogenic perturbations to these systems.

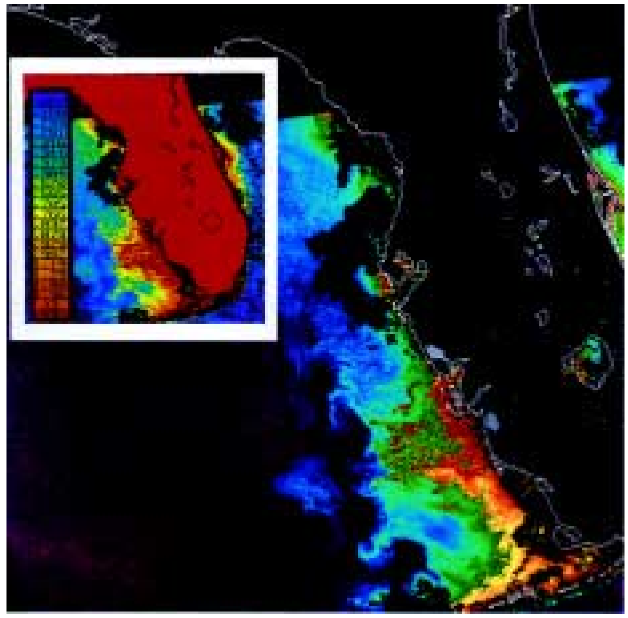
Linked Biological and Physical Dynamics

During intense El Niño events, warm signals propagate poleward along the eastern boundaries of the Pacific. Estuaries, where rivers run into the sea, respond quickly to this change at their mouths, linking global climate to very local environments. Dramatic upset of the oxygen and nutrient levels of an estuary can result. Coupled with these physically induced changes, human activity has increased the nutrient loading in many coastal regions. Even more ominous is the introduction of wildly prolific new species from abroad, transported as ships' ballast. An early example was the invasion of the Derwent Estuary in Tasmania by an aggressive dinoflagellate, *Gymnodinium catenatum,* from Asia. In the US, an entire ecosystem in the San Franscisco Bay was unexpectedly modified by introduction of a single species of Asian clam, which is now dominant. And, transport of *Gymnodinium breve* by the Gulf Stream has carried the 'red tide' from the broad west Florida continental shelf all the way to North Carolina where it infected shellfish (Figure 8).

Public interest in restoring near-shore and open-ocean aquatic systems as close to their natural states as possible requires approaches that integrate and predict the physical environment as well as its biogeochemical components—"whole-system" models. Whole-system models are a frontier with new and diverse phenomena and processes to consider. Advances will be required in data assimilation as well as in description of biological processes such as functional responses, individual behaviors and species interactions, each interacting with physical processes: turbulence in stratified systems and mixing in less-stratified ones. Also requiring incorporation are chemical processes such as air-sea and groundwater-benthic fluxes of nutrients, and geological processes such as sediment transport, biologically mediated armoring and matting, and beach erosion.

Even limited linking of ecosystem and physical oceanographic models offers opportunity for significant increase in understanding of ocean system processes (see Physical-Biogeochemical Model box on page 46). For example, the Bering Sea in 1998 experienced a widespread bloom of the coccolithophore *Emiliani huxleyi*, which replaced normal summer phytoplankton communities. Because coccolithophores are poor food for euphausiids, copepods and benthic infauna, sharp declines in these three groups followed, culminating in the

Figure 8. CZCS image, 14 November 1978, providing an estimate of chlorophyll *a* in ug/L (inset) during a *Gymnodinium breve* bloom off the west Florida coast from south of Tampa Bay to the Florida Keys. When processed at a higher resolution, chlorophyll *a* is detectable at *G. breve* cell concentrations that are not visible to the human eye (i.e. Stump Pass, top arrow, 6.7x10^4 cells/L; Doctor Pass, bottom arrow 4.6x10^5 cells/L). Figure from Tester, P.A. and K.A. Steidinger, *Gymnodinium breve* red tide blooms, Initiation, transport and consequences of surface circulation, *Limnology and Oceanography*, **42**, 1039-1051, 1997. P. Stegmann and K. Carder provided the CZCS imagery.



die-off of thousands of shearwaters that migrate from New Zealand to the Bering Sea to breed. Shearwaters depend on the euphausiids and copepods for food. Grey whales, which feed on the benthic fauna and euphausiids, also were starving. The coccolithophore bloom has occurred again in 1999, which may signal collapse of the Bering Sea ecosystem. It is tempting to link these events to the El Niño-La Niña cycle, but further investigations and modeling are necessary to establish the causes of this unprecedented ecosystem change. Understanding why it happened and predicting future such events here, and in similar ecosystems elsewhere on the planet, is an example of problems calling for biological ocean prediction.

Evidence is mounting that understanding of locally observed variability of physical and biogeochemical cycles is in many cases best addressed by considering processes at basin scales.

Upper Ocean Dynamics, Turbulent Mixing and Convection

The surface mixed layer of the ocean is the layer that directly feels the effect of wind stirring and of buoyancy fluxes resulting from property exchange with the atmosphere. Forecasting the evolution, in space and time, of the mixed layer is perhaps the biggest individual challenge in ocean prediction. An inferior mixed layer in a three-dimensional ocean model not only will fail to represent the near-surface vertical distribution of surface-forced variables such as temperature, salinity and nutrients. It is also likely to fail in predicting the onset, duration and depth of convective overturning events that set the properties of the subsurface water masses and thus affect the thermocline structure and the meridional overturning circulation. Turbulence and flow structures of the scale of the layer depth (fronts and Langmuir cells) greatly complicate the physical behavior of flows. Finding an optimal level of closure for mixed-layer problems should be a top modeling priority.

A Coupled Physical-Biogeochemical Model

Contributed by Karline Soetaert, Peter Herman, Jack Middelburg, and Carlo Heip, Netherlands Institute of Ecology, Yerseke

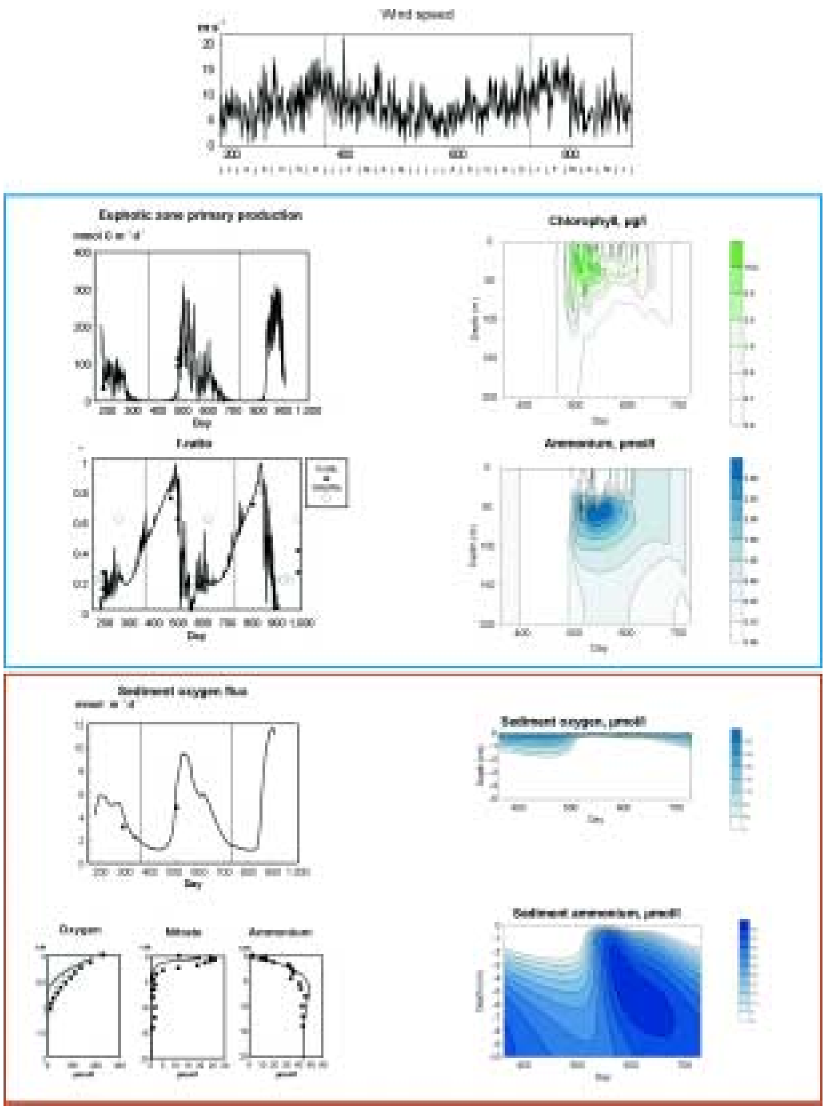
Biological processes affecting carbon and nutrient cycling are highly dependent on the physical structure (mixing, stratification) of the water column. Heating from the top warms the upper water layers, reduces vertical mixing and eventually leads to stratification, whereas cooling and wind shear at the surface destabilize the water column and lead to enhanced mixing. Deep, nutrient-rich water is mixed into the euphotic zone, where nutrients rapidly are used for primary production. A part of the fixed nutrients settles out of the euphotic zone in particulate form and is remineralized in deep, aphotic waters or in the sediment. The remainder is locally recycled through grazing and mineralization and is reused for primary production. Nitrogen fixed by organisms is partly buried upon reaching the sediments, partly removed by denitrification and partly returned to the water column.

We have represented the coupled physical-biological processes in a one-dimensional (vertical), dynamic model. The physical part of the model generates vertical profiles of temperature and eddy diffusive mixing and is forced by wind shear and heat transfer at the surface and by bottom shear in the benthic boundary layer. The biological model considers primary production, grazing by zooplankton, zooplankton development, detritus formation, sinking and mineralization and nutrient transformation. In the sediment we modeled the reactions of early diagenesis involving organic carbon, oxygen, nitrogen and reduced substances such as iron, manganese and sulfide. The model was validated using data from the European Union Ocean Margin Exchange project (OMEX).

Model results show a drastic change in time scale from the meteorological forcing (hourly resolution) via the daily scale response in pelagic variables (chlorophyll *a*, primary production, ammonium, *f*-ratio) to the monthly to yearly scale sediment response. High resolution in meteorological forcing is needed because vertical mixing is much more affected by short bursts of high winds than by continuous low winds. Pelagic variables respond rapidly to these intense mixing events. The slowly responding sediments must be incorporated to include the delayed regeneration and loss of nutrients. Reconciling these different time scales in an efficient and consistent numerical code poses major challenges.

Data-model comparison shows that this type of model can be used to link easily measurable variables (e.g., chorophyll *a* and temperature, which can be obtained from remote sensing) to variables that are of high interest (e.g., the *f*-ratio of new to regenerated production) for which shipboard measurements are usually insufficient to estimate a seasonally integrated value.

Progress in this type of coupled modeling will profit from advances in computing technology, allowing implementation of sufficiently detailed models in three dimensions, and from progress in remote data acquisition, in particular of meteorological forcing of biologically relevant variables such as chlorophyll *a*.



Upper panel (Forcing of system): Time series plot of wind speed. Vertical lines delineate the period shown in detail on the right.
Middle panel (Water-column response). Left: Comparison of model predictions with shipboard measurements (primary production and *f*-ratio) and remote observations (*f*-ratio). Right: Modeled temporal evolution of chlorophyll and ammonium in the water column
Lower panel (Sedimentary response): Left: Comparison of model predictions with benthic lander-based oxygen uptake rates and observed pore-water profiles. Right: Modeled temporal evolution of dissolved oxygen and ammonium in the sediment.

Mixing along and across the layers of the ocean interior allows fluid to rise and sink, and stirs tracers and ecosystems horizontally (see Turbulence chapter). Climate models cannot generally represent this level of detail: it must often be parameterized. To make matters worse, convective plumes penetrate as much as two kilometers downward from the surface, at a relatively few sites where the oceanic stable stratification is weakened and winds are strong and cold. Representation of convection in computer models must be improved.

Global Fresh-Water Circulation and Sea Ice

Understanding the movement of the water and water vapor through the atmosphere-land-ocean system is a key to the thermodynamics and physical dynamics of weather and climate. Both observations and models are particularly weak in this area (it is very difficult, for example, to measure rainfall over the sea, either on a ship or from a satellite). Impacts of freshwater transport on human populations and ecosystems are numerous. Monsoonal flooding, continental drought and milder climatic variation of rainfall all are related to the ocean. The oceanic overturning circulation, described above, is centrally dependent on freshwater loading at high latitudes.

The physical density of ocean water is controlled both by its temperature and salinity. Variations in salinity follow from phase changes: evaporation, precipitation, freezing and thawing near the sea surface, and runoff and iceberg calving from land. Freshwater layers at the surface are very buoyant, and can control both upper-ocean dynamics and the larger scale overturning circulations. Observation and computer modeling of salinity fields must deal with this complex interaction with atmosphere and land surfaces.

Observational data for freshwater input, either directly through snow and rain or indirectly via rivers and terrestrial glacier runoff, can in principle be provided by atmospheric circulation model simulations. However, model biases in handling the terrestrial and the atmospheric components of the hydrological cycle and in particular lags in groundwater inputs make this practice inadvisable.

Sea ice, because of its insulating capacity, its radiative properties and its creation of saline brine during freezing, exerts profound effects on air-sea heat exchange. It is a major factor in high-latitude climate, one that is currently suffering major change in the Arctic (Figure 7). Representation of sea-ice in numerical models is rich with microphysical challenges.

Complex Seafloor Topography and Down-Slope Flows

The geography of the seafloor is rich with seamounts, ridges, transform faults, continental rises and shelves, as well as the occasional flat abyssal plain. Ocean circulation is surprisingly sensitive to this detail, owing to Earth's rotation. The flow is channeled and broken into eddies by the topography, yet once again computer simulations of moderate resolution have difficulty in representing these effects. Seafloor mountains, ridges and continental rises exert horizontal pressure forces which are crucial elements of the circulation.

Water sinks as part of the meridional overturning circulation in narrow streams at high latitude. These are boundary currents hugging the continental rises, a few tens of kilometers wide and often just a few hundred meters thick. As they descend, waters from intermediate-depth layers are entrained into them. Their transport increases, and they drive recirculating flows in the surrounding ocean. Accurate representation of these concentrated overflows has been very difficult to achieve. Their assimilation into the global pattern of circulation is an important goal for modeling.

WHAT MAKES PROGRESS POSSIBLE NOW?

- **Instrument and platform development.** Observations of the ocean are the ultimate source of progress. Remarkable developments in instrumentation during the last few years have put us in a strong position to "know" the complexity of the oceans (see Tools for Observation box on page 52). For *in situ* measurement, compact, electronic and optical sensors can now record temperature, salinity, dissolved oxygen, fluorescence and suspended-particle density. Video imaging provides detailed biological sections and profiles. Sensors for nitrate (an "autoanalyzer on a chip") and carbon dioxide are being developed. Drifting, moored and gliding platforms are available to reduce our dependence on expensive ship time. Nevertheless, some of the most subtle chemical, biological and physical observations continue to require ships as platforms. Remote sensing using satellites and acoustics provides extensive spatial coverage.

- **Rapidly improving computer modeling.** Numerical modeling acts in tandem with observations, theory and laboratory experimentation. Aided by the speed of modern workstations, many research and dissertation projects in physical and biogeochemical oceanography today have a numerical modeling component. With the observational database rapidly growing and sufficient computational resources to support experimentation with a wide variety of models, we are on track to make rapid progress. The time when only major institutions had the resources to engage in ocean modeling, and even then were forced to invest them into the development of a single "super model," has passed. Today's enriched model "gene pool" removes uncertainties associated with dependence on too few models.

  As more and more oceanographers make use of modeling, its diversity is increasing, just as occurred two to three decades ago in meteorology. In modeling the physical circulation, a choice exists today between "level" models which represent approximately the equations of a continuous fluid with values only on a fixed three-dimensional lattice of points, and "layer" models which represent the three-dimensional fluid continuum by a simplified stack of "shallow-water" layers. Likewise, modelers today have a choice of different horizontal grid layouts allowing them to concentrate computing resources in specific geographic regions that may be difficult to resolve spatially, such as undulating coastlines or gaps in underwater mountain ranges.

- **Continuing development of theory.** Numerical models will not in our lifetimes attain sufficient resolution and completeness to describe all of the missing physics of the small scales of motion. The relatively high resolution seen in Figure 3, with 10 km grid spacing, restricts the duration of the model runs, yet it is still a factor 10^7 too coarse to represent the finest (millimeter-scale) motions in fluid turbulence. Even if we could resolve all scales, a "perfect" numerical simulation would be of little value without understanding of basic principles upon which all this detail rides. Theory defines the principles that can simplify the "rules of play" for ocean circulations, waves and mixing.

  While the physical ocean can be described by its velocity, temperature, salinity and sea-surface elevation, other combinations of these quantities have been discovered. The potential density is a combination that describes the organization of the oceans into stable layers. The potential vorticity is another function of these variables that describes quantitatively the tendency of small elements of fluid to spin. Potential vorticity describes much about the flow and the disturbed, undulating layers of potential density. The remarkable fact is that both of these two quantities remain constant, if one follows the moving fluid (until friction or diffusion acts): they are "tracers" of the motion. Maps of potential vorticity and potential density of the oceans show a large-scale geographical variation connected with Earth's shape, and smooth variations related to the circulation of the ocean, with concentrated variations in jet-like currents and eddies. Rossby waves, instabilities and their interaction with the general circulation are all described compactly with potential-vorticity "thinking." Water masses, traveling around the global ocean, are marked by their potential vorticity and their trace chemical "signatures."

Theory also defines simple analogs of the complex ocean system. Henry Stommel created a model of the ocean involving just two boxes of uniform fluid, connected by horizontal pipes. After imposing temperature and freshwater fluxes at the ocean surface, a family of possible circulations occurs. As surprising as it may seem, this box model contains the essence of the chaotic variability of the great meridional overturning circulation of the world's oceans. It has become a paradigm showing the possible slowing of the circulation under global warming, and the multiple forms that ocean circulation can assume.

WHAT IS REQUIRED FOR PROGRESS?

To predict and test the states of the ocean, one needs an ocean model, an observing system, a data assimilation technique and adequate computer facilities.

- **New approaches in physical modeling.** Models are idealizations of reality. Such idealizations are helpful if they remove complexities that stand in the way of understanding the response modes of a dynamical system. Development within complex numerical models is particularly needed in the areas of turbulent mixing and convection; complex seafloor topography and down-slope flows; global freshwater circulation and sea ice; "open" lateral boundaries; and upper ocean dynamics. In addition, simple idealizations of the complex ocean-atmosphere system must be pursued.

- **Improved whole-system models.** Models of biological and chemical processes are essential for prediction and for understanding. Coupled with physical models, they allow exploration of ranges of response that can be realized, the conditions under which particular responses are possible, and thresholds where undesirable responses (e.g., extinction) might occur. At present, biological models generally either track bulk properties (nutrients, phytoplankton, zooplankton, detritus) or individuals (growth, reproduction, death, feeding) in the physical environment specified by the coupled physical model. The approach of developing large ecosystems models should be "middle-out" and not "bottom-up." They should focus first on the taxa of primary interest and elaborate up to predators and down to prey. This structure relies on providing necessary detail of the model for the target species and requires diminishing detail of the neighboring ±1 and ±2 trophic levels. The effort in constructing these models lies in identifying the target species and in achieving proper parameterizations of the processes and interactions with neighboring levels.

A Sea of Change: Hawaii Ocean Time-Series

Contributed by David M. Karl, University of Hawaii

Oceanic productivity, fishery yields and the net marine sequestration of atmospheric greenhouse gases are all controlled by the structure and function of planktonic communities. Detailed paleoceanographic studies have documented abrupt changes in these processes over time scales ranging from centuries to millennia. Most of these major shifts in oceanic productivity and biodiversity are attributable to changes in Earth's climate, manifested through large scale ocean-atmosphere interactions. The establishment of a global network of ocean time-series stations for repeated physical and biogeochemical measurements represents one mechanism for the ecosystem surveillance that is necessary to record and eventually understand these complex oceanic processes.

The open ocean has traditionally been viewed as a nitrogen (N) limited habitat, and this has guided the development of conceptual models of numerous biogeochemical processes. However, under conditions of extreme N-limitation when the more accessible pools of nitrate and ammonium have been exhausted, certain groups of prokaryotic microorganisms can turn to the nearly inexhaustible pool of dissolved N_2 in the sea as an alternate N source.

Observations made during the Hawaii Ocean Time-Series (HOT) program at Station ALOHA (22°45'N, 158°W) during the past decade suggest that N_2 fixation is a dominant source of new N for this ecosystem. Based on measurements of the distribution and abundance of key N_2-fixing *bacteria*, N_2 fixation was estimated to account for approximately 30 to 50% of the total N export, a value equivalent to 50 mmoles of N m^{-2} yr^{-1}. However, this appears to be a perturbed ecosystem state, rather than business as usual.

One hypothesis is that this enhancement of N_2 fixation is a direct result of climate-induced changes to the North Pacific habitat. Selection for N_2-fixing bacteria (including *Trichodesmium*, selected species of *Synechococcus* and perhaps other free-living and symbiotic *Bacteria*) resulted from increased stratification and oligotrophication. This is likely a direct consequence of the increased frequency and duration of El Niño Southern Oscillation (ENSO)-favorable climate conditions during the past two decades in concert with changes in the longer-term Pacific Decadal Oscillation (PDO).

N_2 fixation in the world's oceans could be controlled by the atmospheric deposition of Fe, which itself is a variable, climate-sensitive parameter. Total atmospheric dust transport is also affected by humankind, including population demographics, global economies and land use patterns. These complex natural and anthropogenic interactions provide a mechanism for biogeochemical variability in otherwise "stable and homogeneous" biomes. In this regard, the seascape might be a slave to the landscape, and there is no question that the latter has changed significantly over the past 250 years.

HOT program data synthesis and modeling efforts are already underway in numerous laboratories around the world. A major advantage in working with these extensive, publicly available data sets (http://hahana.soest.hawaii.edu) is the rich spectrum of variability that is observed in an ecosystem that was expected, *a priori*, to be homogeneous and time invariant. These "surprises of the sea" should keep us busy for at least another decade.

Reference

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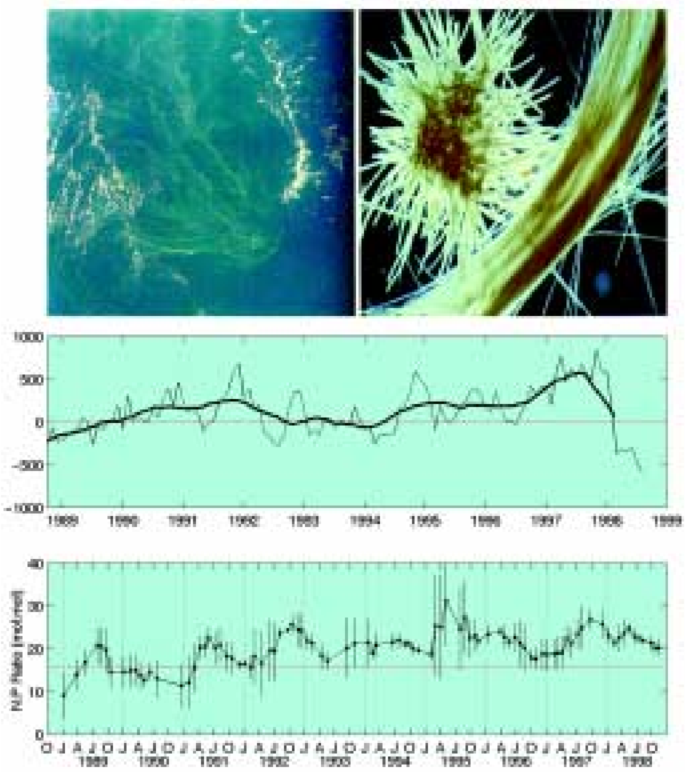


Top left: Surface ocean bloom of *Trichodesmium* as seen from the US Space Shuttle about 300 km above the sea (scale: 1:850,000). Top right: Microscopic view of *Trichodesmium* showing the characteristic spherical (also called puff) and fusiform (also called tuft) morphologies. Center: Troup Southern Oscillation Index (SOI) showing the 10-year running mean (heavy line). The continuous positive SOI (El Niño favorable) condition which for the subtropical North Pacific means fewer storms and less mixing. There may also be gyre circulation effects. These physical features give rise to an extreme oligotrophication (nutrient stressed conditions) and selection for organisms like *Trichodesmium* which can fix their own N from the nearly inexhaustible supply of dissolved gaseous N_2. Bottom: The result is a steady increase in the N:P ratio of materials exported from the euphotic zone. Along with this is a higher than average C:P ratio (P is selectively retained while N and C are exported) causing a temporary change in the balance between export C and imported C (which is imported at the 106C:1P "Redfield" ratio, from below). The net effect is a decadal scale, climate driven temporary sequestration of C which will have major impacts on the flux of carbon dioxide across the air-sea interface.

- **Improved observational sensors and platforms.** The full three-dimensional complexity of the ocean has to be confronted. Improved measurements of many types (e.g., measuring temperature, salinity, currents, phytoplankton, zooplankton, nutrients, oxygen, pigments, transmissivity, carbon dioxide) involving arrays deployed for extended periods are necessary to resolve mean and variance on a seasonal time scale at least, if not on the event scale. Compact electronic sensors for biology and chemistry will give a quantum leap in understanding the ocean. For example, predicting the onset of blooms and areal extent of blooms has practical implications for fisheries and inherent value for integrated ecosystem studies. Increasing sophisticated techniques of molecular biology and multidisciplinary sampling need to be developed to track the genetic evolution of ecosystems. There is a feeling of urgency, particularly regarding the coastal ocean. There we are observing systems that are already embarked on rapid and diverse changes, and are under external stress.

  Satellites give us virtually global observations of sea-surface temperature, sea-surface elevation (hence an approximate global map of the surface currents), surface winds, tropical rainfall, large- and fine-scale surface waves, sea-ice cover and ocean color, relating to biological productivity. Advances in satellite sensor technology promise more (for example, an approximate surface salinity field and global radiometric SST observations through cloud), yet continuing support must be exerted to keep the even current sensors operating into the future. Acoustic transmission, over both long and short range, produces a variety of two- and three-dimensional information.

  The prospect of small, low-power, accurate electronic or optical *in situ* sensors for many chemical and biological variables is exciting. New drifting and propelled Autonomous Undersea Vehicles (AUVs) are under development, which can survey many thousands of kilometers of ocean on a single mission; these at long last will help us to understand the fully four-dimensional covariance in biological and physical processes.

  Given the remarkable suite of new sensors and platforms, resources are needed to deploy them in adequate numbers.

- **Extended time-series observations.** The increasing evidence of long-term change of Earth's climate, and its ubiquitous effects on the oceans, has come from very sparse observations. Only a handful of sites in the world's ocean have been revisited regularly over many years. At the coasts and on islands, some tide gauges have been in operation since the earliest extended measurements in Britain in the early 1800s. A network of weather ships occupied fixed locations in the high latitude Atlantic and Pacific in the 1950s to 1970s, yet only a few fixed sites are still being monitored (see HOTS box on opposite page).

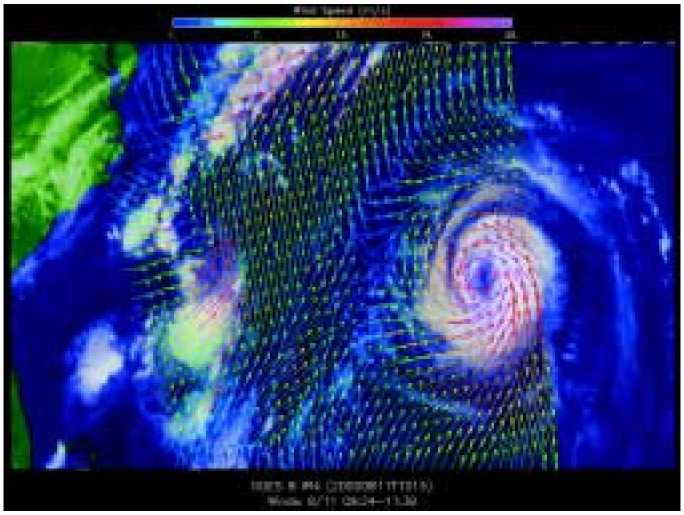
  It would trivialize the sampling problem to suggest merely collecting data at a single point. In a system in constant motion in three dimensions, it is difficult to interpret trends without knowledge of spatial correlation scales. We view the requirement for extended time-series observations to include capturing essential spatial signals as well, posing a significant challenge to experimentalists.

  Quasi-random hydrographic stations have been combined in a heroic work of data "archeology," to construct a 50-year history of the net heat storage of the world's ocean (see Figure 1 in Global Climate chapter). We are, however, generally lacking time histories, and must rely on proxy indicators of climate such as tree rings, sediment cores and ice cores. Manageable surveying of the three-dimensional, time-dependent world would be difficult even without resource limitations. As it is we must identify a small set of locations and sections that merit constant "exploration in time." Fortunately, new tools are rapidly increasing the efficiency of long-duration measurements (see Tools for Observation box on page 52).

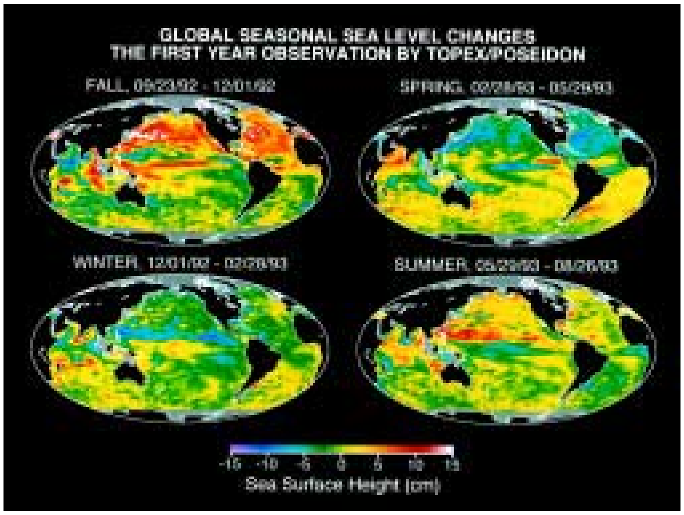
Tools for Observation

Compiled by Peter Rhines, University of Washington

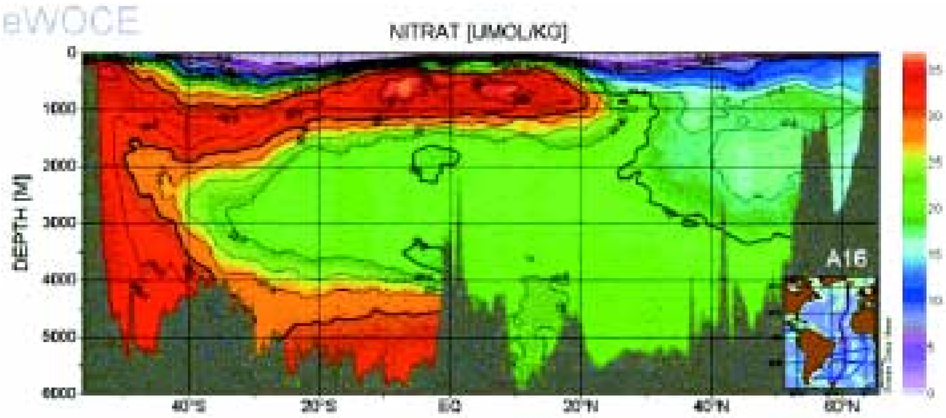
Orbiting satellites provide global coverage, observing sea-surface elevation, surface temperature, ocean color (relating to biological fields), sea-ice cover, surface winds, waves and surface "textures" that relate to circulation.



Hurricane Alberto as seen by Quikscat satellite wind fields (NASA, Jet Propulsion Laboratory). The ability to map surface winds over the entire world ocean, along with sea-surface temperature and many atmospheric fields, is an enormous aid to prediction of wave fields, surface currents and air-sea interaction.



Sea-surface elevation observed from the Topex-Poseidon satellite. The time-averaged sea-surface has been subtracted so that this emphasizes the seasonal cycle and mesoscale surface currents, which are approximately proportional to the slope of the surface. Intense, narrow current anomalies are seen at the equator and near coastal boundaries, and a texture of 100-km scale eddies is seen almost everywhere.

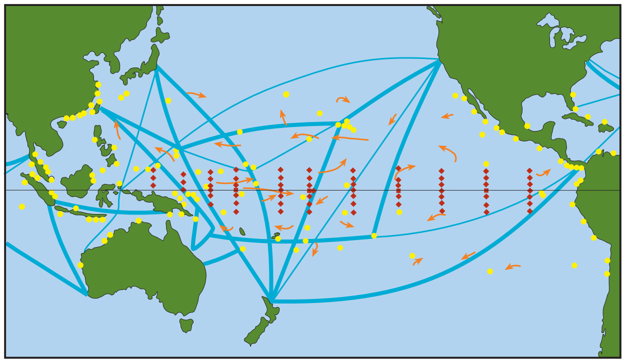


The classic tool of oceanography is the ship, steaming along a line while lowering water-sampling devices and electronic instruments. Here dissolved nitrate is shown in the Atlantic Ocean, along a section from Antarctica (left) to Iceland. High concentrations of this nutrient occur deep in the ocean and in the Southern Ocean. Near the surface, nitrate is almost absent, evidence of active ecosystem growth at the top of the ocean. The global circulation must bring nitrate up to the surface, and controls the distribution of life. New miniaturized sensors are being developed to measure such fields electronically (Figure courtesy of WOCE, plotted by R. Schlitzer).

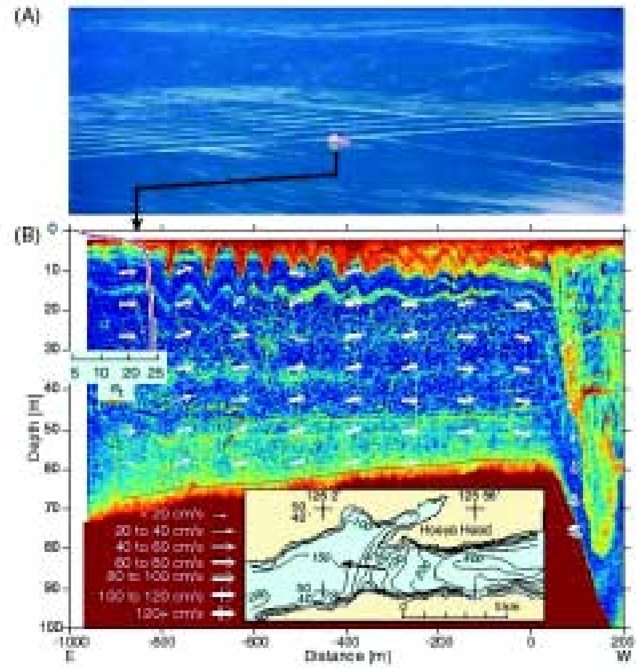
Ships are the mainstay of oceanography. Measurement of biological and chemical fields as well as classic hydrography (temperature, salinity) is carried out with lowered instruments and water samplers. Chemical tracers, natural (such as nitrate) and anthropogenic (such as tritium and CFCs) provide an integrated view of the ocean.

Ship-borne, free-fall instruments provide detailed profiles of ocean mixing and turbulence. Acoustic backscatter instruments provide images of microstructure and profiles of currents.

Moored instruments provide observations extended in time, and anchored to one site. These are particularly valuable in establishing the climatology of regions with intense, narrow currents and temperature/salinity structures.

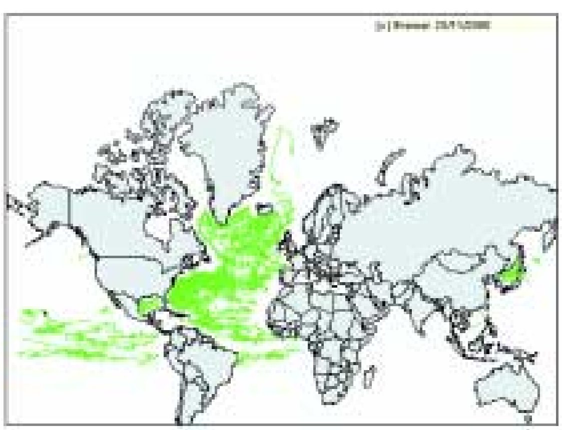


Deep-sea moorings in the equatorial Pacific, maintained by NOAA, have provided a remarkable portrait of El Niño-La Niña cycles. This huge time-series array is augmented with tide gauges at islands, satellite imagery and altimetry, drifting buoys (arrows) and temperature-current measurements from ships (blue lines). Figure courtesy of NOAA/PMEL/TAO Project Office, Dr. Michael J. McPhaden, Director.



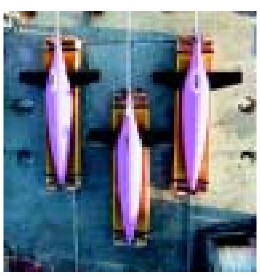
Acoustic profiling and towed temperature-salinity sensors provide "CAT scans" of the upper ocean. Here the Canadian ship, *Vector*, explores the remarkable undular bores that occur where a tidal flow crosses a topographic ridge. The wave crests are seen as slicks on the surface (top) and as a train of "solitons" radiating from the concentrated down-slope flow in a surface-to-bottom section of temperature (bottom). Figure reprinted with permission from, D. Farmer and L. Armi, The generation and trapping of internal solitary waves over topography, *Science*, **283**, 188-190, copyright 1999 American Association for the Advancement of Science.

Freely drifting and "gliding" vehicles profile the ocean while communicating to home base via satellite. In sufficient numbers, PALACE floats and gliders can map out the oceanic temperature and salinity, and they will soon incorporate electronic sensors for oxygen, nitrate and other chemical and biological fields.



Tracks of many ARGO floats as of November, 2000. Along with this path information, profiles of temperature and salinity are recorded. Figure from the Coriolis Data Center, http://www.ifremer.fr/coriolis/palace/geomap.asp.

The ARGO float program involves the deployment of several thousand freely drifting PALACE floats, which profile the oceanic temperature and salinity while moving with the circulation, deep beneath the surface. In large numbers they are yielding a global picture of the evolving density structure of the ocean. Photo courtesy of S. Riser, University of Washington.



The Seaglider is one of several autonomous undersea vehicles that will enable oceanographers to measure hydrographic, chemical and biological fields on long sections across the oceans. This particular instrument can measure about 1000 profiles from the surface to a depth of 2 km over a track of about 6000 km. Each time it surfaces it transmits its data via satellite, at which time its course can be reset. Photo courtesy of C. Eriksen, University of Washington.

- **Merging observational data with models: Data assimilation.** Given an adequate ocean observing system and given continued advances in our modeling efforts, the next step is to use these observations to drive and update models from an "initial value" input in a predictive mode. Plentiful physical data now exists from satellites, and increasingly from drifting-profiling vehicles. Assimilation models for short-term prediction (e.g., in the case of an oil-spill trajectory) and long-term climate (e.g., with the possible slowing of the deep circulation by high-latitude warming and freshwater loading) will one day be the centerpieces of our science. Near-optimal data assimilation techniques require extensive raw computing power.

- **Computers.** Ocean prediction would be impossible without computers. The ocean sciences have reached a point where its progress is severely hampered by the lack of computer resources. Computer and data storage technologies undoubtedly will continue to advance, perhaps even more so in the future than in the past, because of the economic incentive and heightened competitiveness that result from catering to a huge consumer market. Academia, and ocean science in particular, will benefit from this development. We are developing an increasingly complex picture of the ocean as a biological, physical and chemical system. Oceanographers have become steadily more dependent on computers and numerical models as investigative tools to unravel this complexity. The need for computers in oceanography is particularly acute because of the extremely nonlinear nature of many ocean phenomena and the difficulty of making observations. If we are to use observational capabilities wisely and turn observations into a comprehensive understanding of the ocean, then we cannot avoid the use of large, sophisticated numerical models.

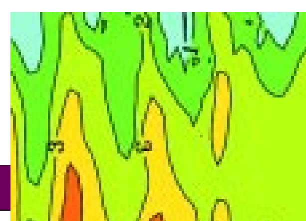
- **People.** Progress in observing, understanding and predicting the oceans depends upon a continuing supply of talented and curious young researchers. The field of ocean science is changing rapidly in sophistication and importance, and new skills will be required to meet the challenges of the coming decades. It is important to recruit, train and imbue with enthusiasm for the field of ocean science entry-level graduate students, engineers and technical workers.

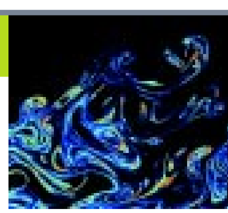
Having the new technologies and carefully considered scientific plans to observe and model the three-dimensional ocean is not the same as actually doing it. The accelerating change of the natural world begs us to pursue these goals with utmost speed.

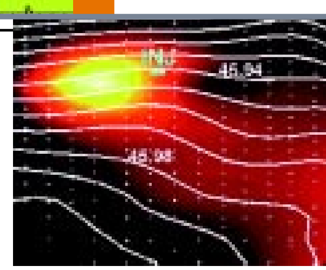
OCEAN TURBULENCE

Ocean turbulence plays a critical role in the transfer of mass, momentum, salt, heat and other water properties from the larger scales of generation or input to the smallest scales of dissipation by molecular processes. Turbulence also has an impact on processes as diverse as zooplankton detection of prey and avoidance of predators, transfer of CO_2 across the air-sea interface, and mixing of heat and nutrients throughout the ocean. A better understanding of ocean turbulence and its role in ocean mixing, and how ocean mixing can be accurately parameterized, is essential for developing new ocean circulation models for studies ranging from local ecosystem dynamics to coupled atmosphere-ocean climate.

Two characteristics of turbulent flow make it extremely difficult to study. First, turbulent flows and tracer fields span a wide range of scales and spatial patterns. The span is so wide that a complete description of the state of a turbulent field would require more degrees of freedom than can possibly be encompassed in analytic theories or, at present, in numerical models. Second, the dynamics of turbulent fields are nonlinear so that each spatial scale interacts with many more and no pattern evolves independently from others. These two characteristics conspire to ensure that the "turbulence problem" cannot be fully solved by the usual analysis technique of simplifying a problem until it can be understood in terms of Newtonian ideas of causality and response. Indeed the combination of complexity and nonlinearity means that the entire web of interacting components must be treated as a whole.







A clear example of the complexity and nonlinearity of the turbulence problem can be found in the overturning circulation of the world's oceans, which is responsible for perhaps half the ocean's ability to transport heat from the tropics toward the poles. Water made dense by vigorous cooling at high latitudes sinks in a few locations and spreads throughout the ocean, forming deep and intermediate water masses. Mass conservation dictates that this water somehow returns to the shallow ocean through the ubiquitous stable stratification. This return requires that the stratifying heat and fresh water be transported downward through this upwelling, presumably by fine- and micro-scale eddies that are small enough not to be suppressed by the stable stratification. By the simple argument that Walter Munk made in his landmark paper "Abyssal Recipes," this balance requires an eddy transport characterized by a diapycnal (across density surfaces) diffusivity of about 1 $cm^2 s^{-1}$. Indeed, general circulation models show that the rate of overturning, and hence poleward heat transport that affects global climate, is largely determined by the diapycnal diffusivity used.

The relationship between overturning circulation and micro-scale eddy diffusion exemplifies three important facts about the broader study of ocean turbulence. First, it shows how all scales are directly connected. The same point is made by considering the upper ocean's carbon pump, whereby the export of particulate carbon scales roughly with the rate at which nutrients are supplied to the euphotic zone to support primary production. Over much of the world's oceans this rate of supply is governed by upward turbulent transport of nutrients through the stably stratified ocean below the winter mixed layer. Second, there is a desperate need for direct observations. The web of nonlinear interactions is so complex that it is simply not possible to reliably estimate the rate of diapycnal eddy diffusion, or of any other important turbulent process, in the absence of direct observations of the turbulence itself. It took decades of observations of eddy motion on the micro-scale and remarkable direct measurements of the vertical spread of tracers (see Brazil Basin box on opposite page) to learn that the ocean's eddy activity is in most places an order of magnitude weaker than is required to produce Munk's 1 $cm^2 s^{-1}$ diffusivity. Third, there is much that needs to be learned. Either the current picture of the overturning circulation is very wrong or mixing is more vigorous at times or places not yet examined than in the places that have been measured. It is fascinating that much the same conclusion is reached about the mixing required to support the observed rates of primary production in the vast oligotrophic oceans (Figure 9), but this paradox is made less striking by uncertainty about the rates and mechanisms of nutrient recycling.

The Brazil Basin Tracer Release Experiment

Contributed by James R. Ledwell, Woods Hole Oceanographic Institution

Cold, dense water is formed at high latitudes and descends to the abyss. How does it start its journey back toward the surface to close the ocean's overturning circulation? To help answer this question, a chemical tracer-dispersion and turbulence-microstructure experiment was undertaken in the deep Brazil Basin. Earlier studies, augmented by the WOCE Deep Basin Experiment observations, documented bottom waters entering the Brazil Basin from the south through the Vema and Hunter Channels, which must upwell across density surfaces to exit the basin. The mass and heat budgets for these bottom waters in the basin implied downward diffusion of heat and buoyancy equivalent to an effective basin-wide diapycnal (across density surfaces) turbulent diffusivity of 3 to 4 cm^2/s. Similarly sized diffusivities have been inferred for other deep basins around the globe and for the abyssal ocean in general. Significantly, these values are much larger than the estimated local diapycnal diffusivities of around 0.1 $cm^2\,s^{-1}$ suggested by a variety of approaches for the interior of the ocean in the main pycnocline.

Microstructure measurements, taken at the start of the Brazil Basin experiment in 1996, implied diapycnal diffusivities on the order of 0.1 $cm^2\,s^{-1}$ all the way to the bottom in the western half of the basin, where the bottom was relatively smooth. But, estimated diffusivities were greatly elevated from near the bottom well into the interior over the rough topography in the eastern half of the basin. To obtain an accurate integrated measurement of the diffusivity in one area of rough bathymetry, a patch of sulfur hexafluoride was released on an isopycnal surface a few hundred meters above the Mid-Atlantic Ridge flank. The distribution of the tracer 14 and 26 months after release was measured (Figure). The spreading of the tracer across isopycnal surfaces yielded a robust estimate of about 3 cm^2/s for the diapycnal diffusivity at the level of the tracer release, a value consistent with our estimates from turbulent dissipation measurements at this depth, after adjustment to account for temporal and spatial bias in the microstructure sampling. The movement of deep tracer toward the east, across isopycnals, implies a much higher diffusivity toward the bottom. The microstructure data suggest that the diffusivity increases by approximately a factor of 3 as the bottom is approached. Extrapolating our estimates to the whole of the Brazil Basin indicates that there may be enough mixing over the rough topography to balance the abyssal heat and mass budgets for the basin.

The energy for the enhanced mixing in the deep Brazil Basin almost certainly comes from shear in internal waves generated by tidal flows over the rough Mid-Atlantic Ridge. Strong evidence for a tidal connection comes from a correlation of the estimated turbulent dissipation rates with the tidal amplitude over the spring neap cycle. Such tidal flows are ubiquitous in the ocean globally. Moreover, the topography in the eastern Brazil Basin is similar to the flanks of the globe-encircling mid-ocean ridge system. This suggests that significant abyssal mixing is widespread. The Brazil Basin experiment has brought us closer to understanding the overturning circulation in the ocean. In particular, it has pointed the way for further examination of ocean mixing mechanisms, other areas of the ocean with different roughness and flow characteristics, and other depths.

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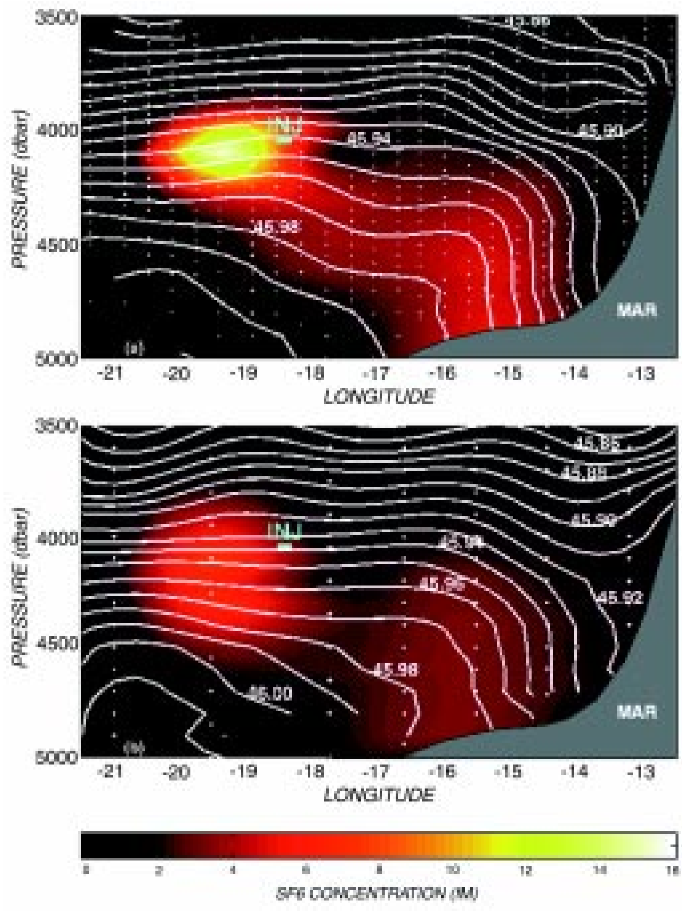


Sections of tracer concentration and potential density from the latitude of the tracer release. Top:14 months after release. Bottom: 26 months after release. The blue bar labeled 'INJ' shows the initial tracer patch. The bathymetry is a polynommial fit to the soundings from the 14-month survey along the zonal valley from which these data were taken. The depths where the white density contours (in kg/m^3) bend sharply down indicate roughly where the valley is enclosed by ridges to the north and south. The colors show tracer concentration: 1 fM = 10^{-15} M. (Reprinted by permission from *Nature* (Ledwell et al, 2000, see above) copyright 2000 Macmillan Magazines Ltd.).

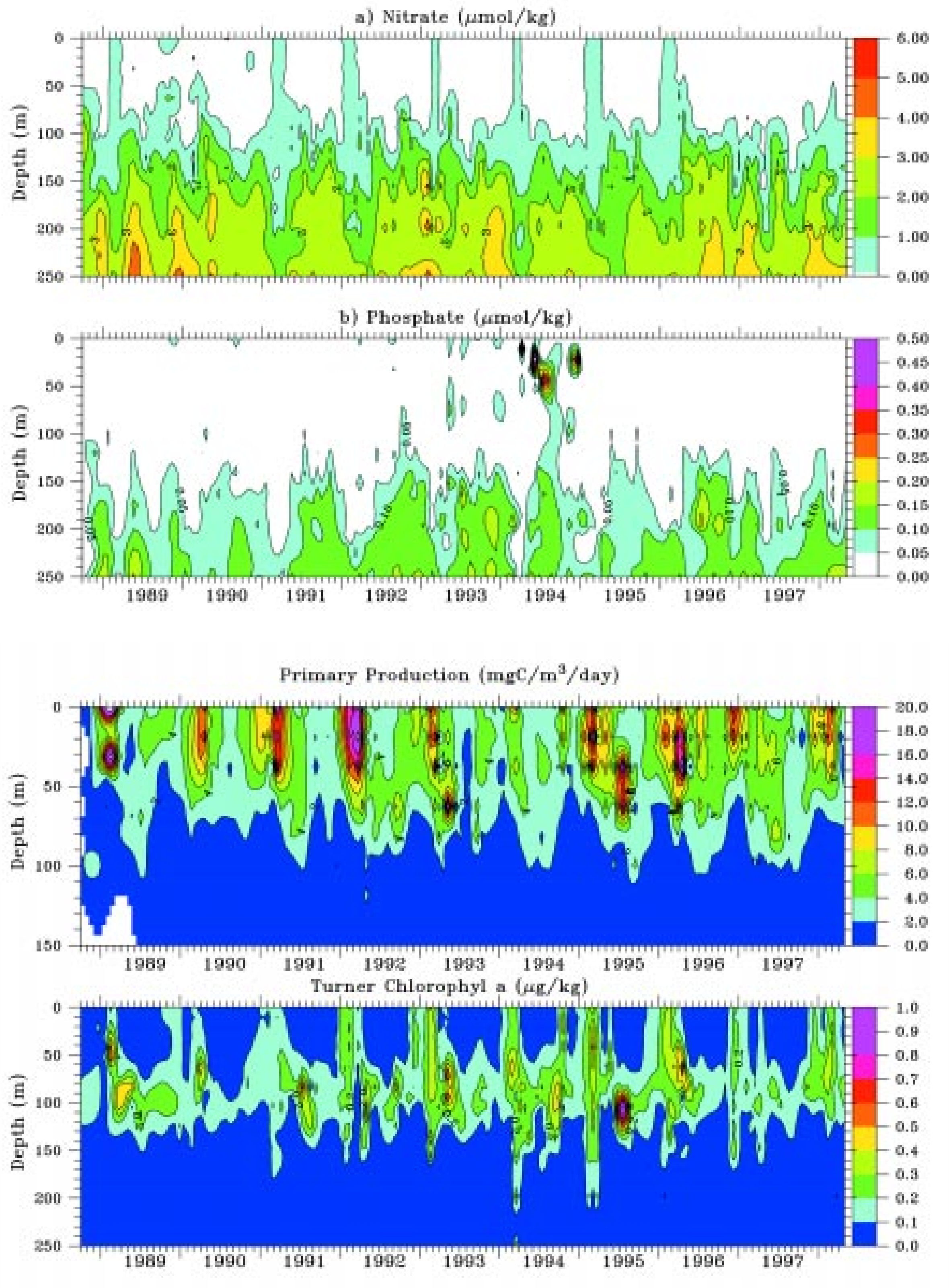


Figure 9. An example of annual variations over the past decade in (a) nutrient concentrations; and (b) pigment concentrations and primary productivity at the U.S. JGOFS Bermuda Atlantic Time-Series Study (BATS) station. Nutrients are mixed upwards into surface waters through eddy diffusion throughout the year; convective overturn deepens the mixed layer during Fall/winter leading to further mixing. Figure modified from Steinberg, D.K., C.A. Carlson, N.R. Bates, R.J. Johnson, A.F. Michaels, and A.F. Knap, Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS): A decade-scale look at ocean biology and biogeochemistry, *Deep Sea Res. II*, in press.

WHAT ARE THE BIG PROBLEMS?

Because turbulence is involved with so many of the processes going on inside the ocean, a comprehensive list of problems to be solved about turbulence would be very long. It is more efficient at the present level of understanding to identify important broad areas of research and explain how they have an impact on understanding in other areas of oceanography.

Diapycnal fluxes

An accurate representation of diapycnal eddy fluxes is needed to reliably model or diagnose large-scale processes such as the ocean's role in climate or the oceanic carbon cycle, as well as better understand overturning ocean circulation, nutrient supply to the euphotic zone, and intentional deep-water disposal of carbon or radioactive wastes. Recently, encouraging progress has been made in relating diapycnal fluxes to the gross stratification, internal wave activity and to roughness on the neighboring ocean bottom (see Coastal Mixing box on page 60). Nevertheless, an understanding of the relative importance of different phenomena (e.g., tides, beams of internal waves intersecting topography, double diffusion, intrusions, internal wave overturning vs. shear, fronts) in establishing diapycnal diffusion is still a remote goal.

Diapycnal mixing is difficult to study because the turbulence required to transport nutrients from below the thermocline, for example, is extremely intermittent in time and space. This intermittency not only makes it difficult to characterize the transport processes going on in one region on a single day, but it causes the transport on another day or in a neighboring region to be different by an order of magnitude. Furthermore, the observations needed to measure turbulent fluxes are extremely demanding technically. Consequently, a geography of ocean mixing is grossly incomplete and there are still vast ocean regions, seasons and depth ranges in which there is little idea of mixing rates.

To better understand diapycnal eddy fluxes requires an increased deployment of autonomous instruments that can provide the long records needed to explore rare events. These same instruments provide a capability for adaptive search and resampling strategies upon encountering unusual values of nutrients or pigments. They will afford the opportunity to confirm the existence of, and measure the temporal and spatial scales of, important vertical transport events. Key in this development will be the successful miniaturization of optical and chemical sensors of nutrients, pigments and particle sizes and types.

Progress can be expected from continued observational exploration of turbulence levels in different regions over the full seasonal cycle with enough observations taken to characterize rare events, and new observational efforts to measure more directly turbulent fluxes of momentum and water properties such as heat, salt and biota. Continued model studies of the effect on the circulation and its biota of different rates of mixing will both explain the consequences of diapycnal mixing and guide observational studies to important regions.

Dye and Microstructure Studies in the

Coastal Mixing and Optics Experiment

Contributed by Neil S. Oakey, Bedford Institute of Oceanography, Canada, and James R. Ledwell, Woods Hole Oceanographic Institution

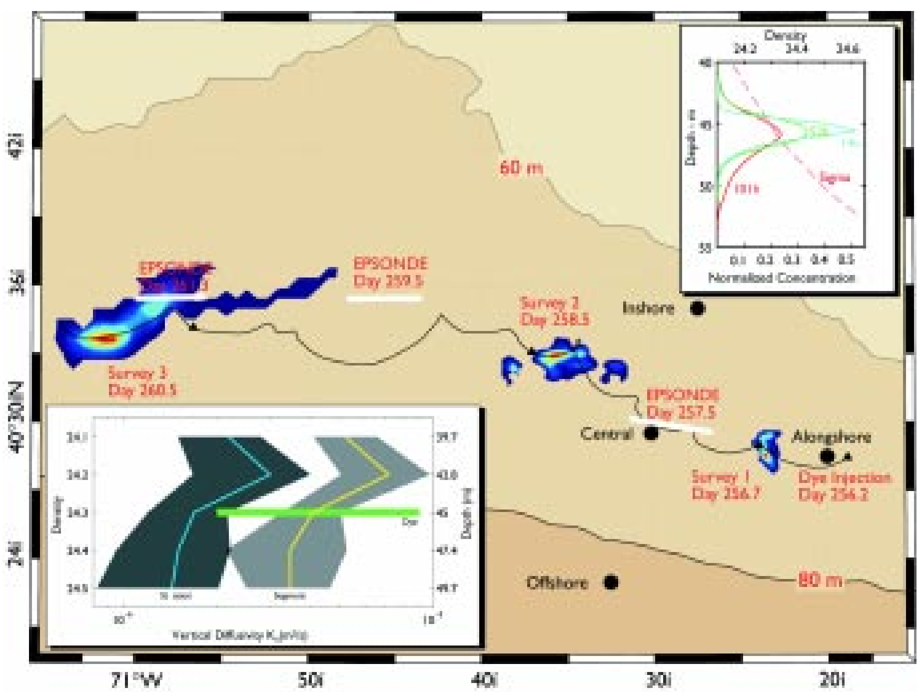
The rate at which quantities such as heat, salt or nutrients are mixed across density surfaces and through the water column is parameterized by the vertical (or diapycnal) diffusivity. For the first time, on the same length and time-scales, diapycnal mixing has been studied simultaneously using two very different techniques, dye and microstructure measurements. A total of four dye and microstructure comparisons were made in the New York Bight area in two field programs in September 1996 and August 1997.

Ledwell determined diapycnal mixing rates using a tracer dye injected at a target isopycnal surface. Diffusivity was estimated by repeatedly sampling the patch of tracer to determine how the concentration of dye evolves in space and time. The evolution of dye injected in September 1996 is shown in the figure. Red indicates the highest concentration of the vertically integrated dye and dark blue the most dilute. The vertical distribution of tracer was obtained by averaging over the horizontal dimensions of the patch with reference to the target isopycnal surface. The vertical dispersion of the dye over the experiment is shown in the upper right inset for the three surveys. Assuming that at each sampling one is able to account for total amount of tracer injected, the time rate of change of the second moment of the thickness of the tracer patch gives the diapycnal diffusivity.

Although the dye gives *the answer*, it tells us little about the processes that cause the mixing. To address this, Oakey concurrently measured vertical mixing rates using a microstructure profiler, EPSONDE. Over 500 microstructure profiles were acquired in 56 hours of sampling at the three sites shown in the figure as broad white bars (centered at day 257.5, 259.5 and 261.3), closely correlated in space and time with the dye measurements. Vertical diffusivities of heat, K_T, and mass, Kr, were estimated from the temperature gradient microstructure and the turbulent dissipation, respectively. Different techniques of obtaining an *ensemble average* from the microstructure results were used to compare microstructure estimates to those from the dye. As an example, K_T is shown in the figure inset. The yellow profile with light gray error bars was obtained by averaging the vertical diffusivities for every 1.6-m vertical *segment* of data. The blue curve with its dark gray error bars was obtained by averaging the temperature variance and mean gradient separately for each 15 to 20 profiles acquired in one transit of a site line (a *station*) and then dividing to obtain vertical diffusivity.

The vertical diffusivity calculated from the diapycnal dispersion of the dye is shown as a green bar (indicating the confidence interval) in the lower left inset overlaid on the estimates of K_T from microstructure measurements. Microstructure profiles interpreted with simplified turbulence models have traditionally been used to estimate mixing rates. Showing that dye and microstructure techniques yield similar estimates of vertical diffusivity gives us more confidence in using the more widely available results from microstructure studies. In general, the dye and microstructure results from all four experiments agreed in that they provided the same mixing rates within the errors of the measurements. The caveat is that the error bars are large - typically at least a factor two for each type of measurement.

This work was funded by the Office of Naval Research as part of the Coastal Mixing and Optics Experiment.



Turbulence, particle contact rates and biological behaviors

Turbulence moves suspended particles as well as fluids, strongly influencing the interaction rates of organisms in life processes such as fertilization of egg by sperm, ingestion of prey by predator or infection of host by pathogen. Success of all such encounters is highly, and often nonlinearly, dependent on the number of organisms in close proximity, and so is strongly influenced by the stirring and mixing effects of turbulence at virtually all scales (see Hydromechanical Signals box on page 62). Abalone populations have been observed to fail in fertilization despite high individual growth rates, for example, when populations fall below critical threshold densities for sperm-egg encounter.

The last decade has seen a rapid increase in understanding of how the kinetics of encounter are influenced by small-scale turbulence in the same manner as is the collision and coagulation of non-living particles. Higher turbulence intensity at a given concentration increases encounter rate, but the shear developed at the highest dissipation rates may be strong enough to prevent consummation of the interaction, just as it may be strong enough to cause disaggregation of inanimate particles. When the concentration of organisms is held constant in laboratory flow devices, fertilization, suspension feeding and larval settlement all are most successful at intermediate shears. In the field, however, turbulence is also dispersive and so acts to eliminate patches of high abundance.

At present, there is a basic understanding of the mechanism by which turbulence effects biological encounter and the rough shape of the unimodal curve describing the rate of successful encounter as a function of turbulence intensity. The next decade promises success in predicting the magnitude as well. The critical questions here include:

1) What are the appropriate length and time scales for interactions among organisms of different sizes, with different swimming behaviors, and with a variety of sensory modalities?

2) How does organism age, size and swimming speed modulate the effect that turbulence has on predator-prey interactions, suspension feeding and aggregation?

3) The biological processes of foraging in any organism can be split into functional components of predation such as search, encounter, pursuit, capture and ingestion. How and at what scales does turbulence affect each of the processes?

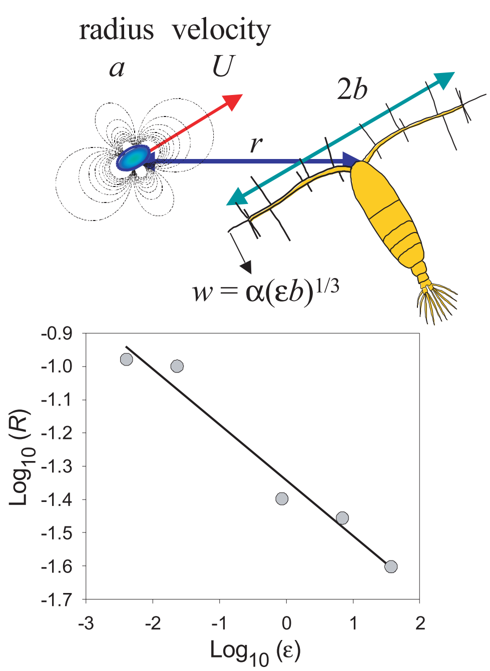
4) Patchiness in the plankton can be caused by purely physical means, but plankton aggregations occur through interaction between behavior and physics. At what turbulence intensities does behavior have the opportunity to control the position of plankton in the water column and how often and when does this opportunity occur in nature?

Hydromechanical Signals and Turbulent Noise

Contributed by André Visser and Thomas Kiørboe, Danish Institute for Fisheries Research

The marine environment is sparsely populated. Remote hydrodynamic detection is critical in finding mates, capturing prey and escaping predators. Copepods for instance are equipped with an array of sensory hairs (setae) along their antennules that give neurological responses at velocity differences (tip to base) as small as 20 µm/s (Yen et al. 1994). But can this sensitivity be used in the presence of turbulence?

It is possible to deduce scaling laws for propagation of hydromechanical disturbances. At low Reynolds numbers (*Re*), for passive sinking or for a feeding current, the associated hydromechanical velocity u attenuates very slowly with distance r as $u \propto aUr^{-1}$ where a is the length scale of the organism and U is its velocity relative to the fluid. This stokeslet flow is associated with one net force on the fluid: drag for the sinking particle and thrust for the feeding current. A self-propelled organism at low *Re* exerts equal and opposite forces on the fluid (drag and thrust), generating a stresslet flow with $u \propto a^2Ur^{-2}$. At high *Re* a self-propelled organism generates a hydromechanical disturbance that conforms to a potential flow beyond the laminar boundary layer. It has the form, $u \propto a^3Ur^{-3}$. Given measured sensitivities of copepods to hydromechanical signals, scaling laws for the remote detection by zooplankton can be deduced (Table). Passively settling particles at low *Re* can be sensed very distantly, with great implication for the interception of particulate fluxes.



Estimated reaction distance R (cm) as a function of dissipation rate e (cm^2/s^3) for the copepod *Acartia tonsa* feeding on the ciliate *Strombidium sulcatum* in the laboratory (Saiz and Kiørboe, 1995). Reaction distance was estimated from observed clearance rates b_o by numerically solving the encounter equation $b_o = p R^2 (U^2 + 2 a^2 (e R)^{2/3})^{1/2}$. The Kolmogorov scale ranges from about 1 mm to 100 mm, greater than or equal to the length of *A. tonsa*.

Turbulence is an appreciable environmental factor for plankton, particularly in its role in enhancing planktonic encounter rates. This is the up side of turbulence. On the other hand, it interferes with detection of hydromechanical signals, thus reducing effective detection distances for particular motility classes. Hence, encounter success peaks at intermediate turbulence intensity.

In still water (turbulent dissipation rate, $e = 0$) a copepod with inherent sensitivity s_0, can detect a swimming ciliate (Figure) at a detection distance $R(0) \propto a(U/s_0)^{1/2}$. The effect of turbulence is to introduce uncorrelated velocity fluctuations between the body of the copepod and the setae positioned along its antennae. With each antenna of length b (calculated for the case where b > Kolmogorov scale), the magnitude of the turbulent velocity fluctuations at the antenna tips is given by $w = a\,(e\,b)^{1/3}$ where a is Richardson's constant ($\cong 1$). For detection, assume that the ratio of the signal (*i.e.*, from the swimming ciliate) to noise (turbulence) must exceed a constant k. Combining terms, $R(e) \propto (Ua^2/a\,k\,(e\,b)^{1/3})^{1/2} \propto e^{-1/6}$, in remarkable agreement with experimental results (Figure).

Although hydromechanical signals provide feasible means to gain information on neighbors, these signals must be "heard" above the background turbulent "noise." The functional form of the detection distance means that the detection of different modes of motility is susceptible to turbulent interference to differing degrees.

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Flow regime and motility mode			$a << b$	$a \quad b$
Low *Re*	Sinking particle or feeding current		$a\frac{U}{s}$	$\left(ab\frac{U}{s}\right)^{\frac{1}{2}}$
	Self-propelled organism		$\left(a\,\frac{U}{s}\right)^{\frac{1}{2}}$	$\left(a^2b\frac{U}{s}\right)^{\frac{1}{3}}$
	Inanimate particle in a feeding current		$\left(a^3b\frac{U}{s}\right)^{\frac{1}{4}}$	
High *Re*	*E.g.*, attacking fish or escaping copepod	Fore	$\left(a\,\frac{U}{s}\right)^{\frac{1}{3}}$	$\left(a^3b\frac{U}{s}\right)^{\frac{1}{4}}$
		Aft	$a\frac{U}{s}$	

Scaling of detection distance for various motility modes. U is the speed of the translating body and a is its radius. The detector length is b, and detection is triggered when the velocity difference between it and the fluid exceeds threshold sensitivity s.

To make considerable progress in answering these questions over the next decade requires new technologies and better computer models. Measuring swimming performance and turbulence intensity simultaneously using new optical technology, for example, is essential to examining the role of turbulent mixing in affecting the migration behaviors of primary producers such as dinoflagellates as well as phytoplankton-zooplankton encounters. Expanded technology in chemical analysis and computer modeling of chemical function is enabling a better understanding of chemosensing, which marine organisms use for feeding and reproduction. Computer modeling and visualization (Figure 10) of the chemical fields produced in a turbulent fluid is also aiding understanding, especially when explicit modeling of organism behavior is superimposed. Relatively simple reaction-diffusion models of biased random walks of predators seeking and consuming prey already have met with success in modeling terrestrial population interactions (e.g., of ladybird beetles with patches of their aphid prey), and the form of these equations transfers readily to the fluid realm. The next decade thus promises to extend much further the predictability of the effects of fluid motions on individual-individual encounters of all kinds. These small-scale effects of turbulence thus give insight into how climate change, by fluctuations in storm frequency or stratification, can affect encounter rates of organisms, emphasizing once more the range of scales over which turbulent mechanisms operate.

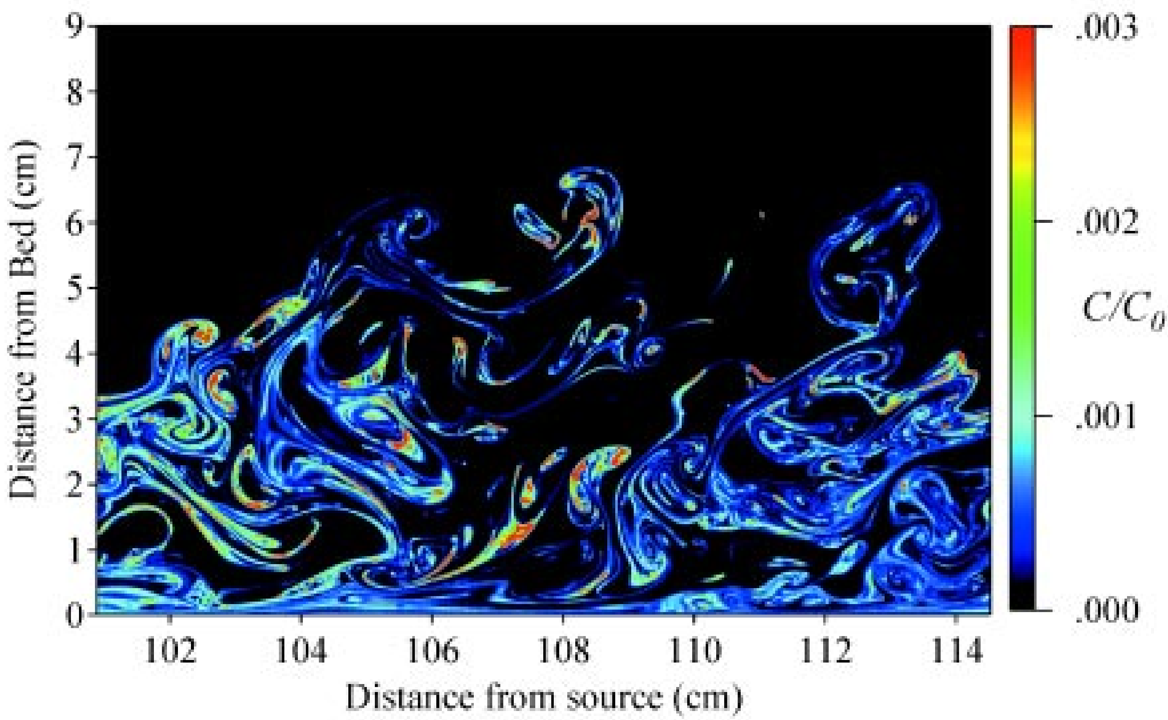

Figure10. Visualization of a thin vertical slice through a laboratory-scale odor plume developing in a turbulent boundary layer; the false color indicates normalized odorant concentration. The odorant is a laser-fluorescent dye released from a flush, low-momentum source upstream of the image. Flow is 10 cm s-1 from left to right. Note the odorant that is trapped in the viscous sublayer close to the bed, and the clear visualization of the turbulent burst-sweep cycle higher up. Consider how an organism might locate and arrive at the source of this odorant Image courtesy of John Crimaldi, Meg Wiley, and Jeffrey Koseff in the Environmental Fluid Mechanics Laboratory , Department of Civil and Environmental Engineering at Stanford University. Research supported by the DARPA-ONR Chemical Plume Tracing Program, directed by Keith Ward.

Mesoscale eddy transport

Mesoscale eddies are energetic, rotating flow features having dimensions from kilometers to hundreds of kilometers. Although intermittent in time and space, mesoscale eddies can exist for months to years and move hundreds to thousands of kilometers in their lifetime. Due to their relatively large volumes and longevities, these eddies can transport large amounts of salt and heat and the planktonic communities over large distances from one oceanic environment to another. Large rings of warm water, spun off from the Gulf Stream, are one common eddy feature of the North Atlantic Ocean, and they often contain biological assemblages transported far from their home, with gradually altering ecosystem-rate processes as ecological succession proceeds.

Mesoscale eddies are strongly affected by Earth's rotation and ocean stratification, and are both generated by larger currents, such as the Gulf Stream and Kuroshio, and are capable of influencing those currents as they shed energy into eddies and as the eddies steer the parent flow. These eddies create shear as they move through the ocean, and this shear produces important fine-scale structures both directly and through interaction with internal waves.

For over 30 years there has been lively debate among physical oceanographers as to how mesoscale eddies affect the larger-scale, more slowly evolving general circulation of the ocean. Henry Stommel first drew attention to this problem, and subsequent observational work has been successful in identifying many of the more energetic classes of surface and subsurface mesoscale eddy motions. The large number of eddies, and the contrast in their energies and properties with the surrounding fluid, make it clear that these eddies can contribute significantly to larger-scale property transport. It is also clear that the correlations of velocity and tracer concentrations (such as temperature and carbon dioxide) are too low in general to be reliably measured at a point with present techniques, thus preventing direct calculations of eddy fluxes. Nevertheless, recent efforts to parameterize these effects have shown that even small correlations between velocities and concentrations can lead to net transports that have a profound effect on circulation and large-scale distribution of properties in the ocean.

In cases where there is a clear separation of spatial scales between eddies and the mean field in which they circulate, recent theoretical work has shown that the eddy flux of a tracer can be modeled as the product of a tensor diffusivity and the tracer's mean gradient. This result has allowed improved parameterizations for eddy fluxes in medium-resolution numerical ocean circulation models (which do not permit resolution of the mesoscale eddies themselves). Clearly, more work using numerical circulation models that either resolve the eddy field directly or incorporate more accurate parameterizations of eddy fluxes are needed to investigate the effects of the mesoscale eddy field on the larger-scale ocean circulation and property distributions. Also required for significant progress are new field measurements of sufficient duration and spatial coverage to establish the magnitude of eddy fluxes and to test the relation of these fluxes with the larger-scale circulation and property distributions. Such measurements can be made within the context of the long time series needed to support climate studies.

Surface-layer processes

The oceanic mixed layer, where turbulent mixing overcomes stable density stratification, is the most prominent consequence of the vigor of air-sea interaction (see Effects of Surface Waves box on page 66). The main energy source for upper-ocean turbulence is atmospheric forcing both by wind stress and buoyancy loss through evaporation and cooling. In turn, this turbulence regulates both the rate at which the ocean responds to atmospheric forcing and how it feeds back on the atmosphere. Because the ocean's immediate impact on the atmosphere is determined by the sea-surface temperature, which modulates the transfer of sensible and latent heat, the cycle of heat storage in the mixed layer and its subsequent release are crucial. It is the slower interaction of the mixed layer and the seasonal thermocline below, however, that governs how the atmosphere affects the stratified ocean. The rate of gas transfer through the air-sea interface is so strongly hindered by that interface's suppression of turbulence that it is plausible that the air-sea transfer of oxygen and CO_2 are mainly determined by the breaking of capillary ripples and plunging waves.

The basic annual variation of the mixed layer's depth and temperature can be understood in terms of air-sea fluxes of heat and mechanical energy and turbulence where the mixed layer meets the seasonal pycnocline. Because of the importance of this seasonal cycle to both the ocean's effect on the atmosphere and establishment of upper-ocean stratification, this process has been widely studied, and several models of mixed-layer behavior are included in ocean circulation models. Remarkably, despite 30 years of measurement and modeling, there is no consensus on (a) what processes are responsible for wind mixing of the mixed layer (how much is wind mixing similar to mixing next to a solid surface, how much is it influenced by breaking waves over scales ranging from micro-breakers to plungers, and how much is wind mixing the result of Langmuir circulations driven by surface waves), (b) what processes, in addition to the obvious buoyancy input by surface warming, cause the deep winter mixed layer to restratify, and (c) what is the relative importance of wind-driven turbulence, large eddies in the mixed layer, and turbulence generated by the strong shear found in the upper thermocline to entrainment of stratified waters into the mixed layer? Much of the seasonal air-sea transfer of heat, for example, is often the result of a small number of storms. It is important even to climate dynamics that these questions are resolved because the ocean's response to such storms differs significantly between models based on these different processes.

Computer modeling using Large Eddy Simulation (LES) techniques can help explain observations and point the way to parameterizations that allow upper-layer physics to be represented in circulation models. However, LES runs into many of the same problems experienced in numerical models when many of the processes responsible for the mixing fall below the grid scale, especially near the surface. Nevertheless, significant progress will depend on sophisticated and comprehensive field studies that not only describe the bulk changes associated with air-sea interaction but also allow detailed diagnosis of the small-scale processes that bring about these changes. Because of the close connection between primary productivity, turbulent nutrient supply and sinking fluxes of particulate carbon, co-locating studies of the physical and biological processes occurring in the upper layer will be a particularly productive path to progress.

Effects of Surface Waves on Oceanic Turbulence

Contributed by Mark A. Donelan, University of Miami

Most of the energy delivered to the waves from the wind is transferred locally to the surface waters through the process of wave breaking. The power delivered to each square meter of the surface varies from 1.6 milliwatts in light winds to 4 watts in strong winds. By comparison, the annual average direct solar radiation absorbed by the ocean surface is 168 watts m^{-2}. Thus the mechanical energy delivered from atmosphere to ocean is small compared to the direct solar radiation. In general, insolation acts to stabilize the surface waters through warming, reducing their density compared to the underlying waters, whereas the mechanical stirring by wind action keeps the surface waters well mixed. The stabilizing effect of the average solar heating rate is easily overcome by mechanical energy from the wind, however, requiring less than a milliwatt m^{-2} of mechanical energy to keep near-surface waters well mixed. Thus, diurnal thermoclines are formed in light winds accompanied by strong solar heating, but are easily erased by convective cooling at night and/or by moderate winds. The seasonal thermocline, being at depths of 50 to 200 m, is insulated from the direct mixing action of wave breaking.

The action of wave breaking delivers energy and momentum to a depth of order the wave height. The flux of momentum sets up a vertical current shear and organized motions, such as Langmuir circulations, that produce mixing to greater depths, eventually deepening the thermocline. Entrainment of the quiescent (or at least weakly turbulent) fluid below the thermocline by the more turbulent fluid above requires enough kinetic energy to overcome the buoyancy gradient at the thermocline, i.e., to increase the potential energy of the fluid. In moderate and strong winds wave breaking injects turbulent kinetic energy into near-surface layers that is more than adequate to the task of mixing typical thermocline density structures. However, kinetic energy from wave breaking decays rather rapidly with depth, and the extent to which wave breaking processes are felt at the thermocline is a subject of much active interest.

The figure illustrates measurements of turbulent kinetic dissipation under breaking waves as observed in a large temperate zone lake by Terray et al. (1996). The most striking aspects of these results are the great enhancement of the dissipation rate near the surface over that expected in wall-bounded flows and the more rapid decrease with depth. Much of the kinetic energy injected by wave breaking is eventually lost locally to heating and so the effect of wave breaking on the upper mixed layer depends on the residual vertical transport of the turbulence (e.g., Monismith and Magnaudet, 1998), the generation of internal waves and their interaction with the thermocline, and such secondary flows as Langmuir circulations (Plueddeman et al., 1996).

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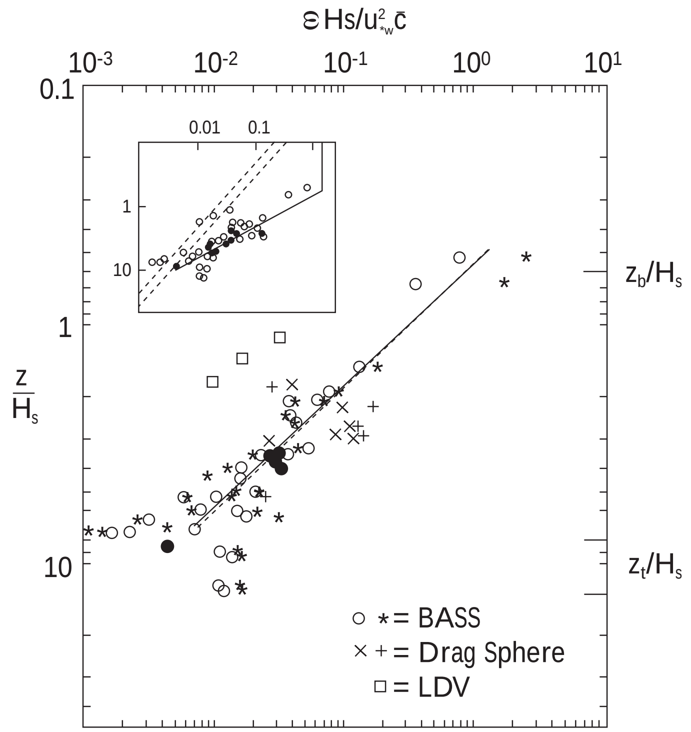

Normalized dissipation rate versus depth, z normalized by the significant wave height, H_s. The line has a slope of –2 in contrast to the expected slope (-1) characteristic of wall layer scaling. The inset shows the data in relation to the expected depth dependence (dashed lines) in a wall-bounded layer.

WHAT MAKES PROGRESS POSSIBLE NOW?

There are no direct solutions in sight to the problems of oceanic turbulence. It is unlikely that a single solution will suddenly solve the turbulence problem that has vexed the brightest minds for two centuries. There are, however, some new tools that promise significant progress. Some of them are:

- **Deliberate tracer releases.** The North Atlantic Tracer Release Experiment was a significant breakthrough in determining very directly the rate of diapycnal mixing in the main thermocline. Because of ingenious methods for releasing the tracer SF6 very close to an isopycnal and for detecting it in very small amounts over large areas, it is now possible to watch diapycnal mixing redistribute a passive tracer for over one year in the interior of an ocean circulation gyre where mixing is quite weak. Deliberate tracer releases have now been successfully made in much more energetic mixing regimes (e.g., a coastal tidal mixing front) to investigate diapycnal mixing on shorter time scales (e.g., several days).

- **Expanding capability for numerical simulation.** The present generation of computers allows limited simulation of turbulent processes and thus provides new opportunities to develop theories and parameterizations of turbulent processes and to better understand what the necessarily incomplete measurements mean. For example, Large Eddy Simulation of the mixed layer is being used to address the questions surrounding mixing within the mixed layer and entrainment of pycnocline water. Likewise, Direct Numerical Simulation is being used to investigate mixing on the smallest scales (down to dissipation scales) and explore the assumptions of isotropy so often used in interpreting instrumental (especially fine- and microstructure) records.

- **Improving sensors and methods for physical observations of turbulence.** The sensor technology that has made present understanding of ocean turbulence possible was, to a large degree, supported for its ability to detect submarines. Despite reduced funding for technical development, this technology has improved steadily so that it is now possible to sample quickly many turbulence variables simultaneously over much of the water column. The ability to sample both velocity and tracer microstructure is essential to providing confidence in the conclusions about transport rates and mechanisms.

- **Improving sensors and methods for turbulent flux measurements.** Accurate direct covariance measurements of turbulent fluxes of momentum and heat are now possible using new acoustic current meters and anemometers. Originally developed for ocean sediment transport and atmospheric planetary boundary layer studies, these new sensors and techniques are beginning to provide a detailed look at the true turbulent fluxes without *a priori* assumptions about isotropy or approximations in the turbulent kinetic energy equation (see Turbulence Dynamics box on page 68). These new flux measurements will provide critical tests of existing and new turbulent flux parameterizations.

New Measurements Elucidate

Turbulence Dynamics in Wave-Driven Currents

Contributed by John Trowbridge, Woods Hole Oceanographic Institution

Breaking waves on beaches drive alongshore currents that reach or exceed 1 m/s, among the fastest oceanic flows. These currents are important because they produce the so-called coastal "river" of sand, typically transporting hundreds of thousands of cubic yards of beach material alongshore past any given position each year, with the potential for dramatic coastal erosion or accretion. Wave-driven currents on beaches are also important in military operations and because they transport and disperse pollutants.

Although the wave-induced driving mechanism has been known for thirty years, the processes that counter the effects of breaking waves, permitting a "force balance" that controls the magnitude and distribution of wave-driven currents, have remained obscure. Most researchers believe that the dominant effect balancing the wave-induced forcing is drag on the seafloor. They further argue that this drag force is transmitted throughout the water column by turbulent eddies, which are far weaker than either the breaking waves or the alongshore currents, but are nevertheless an effective agent for transmitting momentum. Although the vertical transport of drag by turbulence is an essential element of conceptual and quantitative models of surfzone processes, it has never been measured directly, because instrumentation and methods of analysis sufficient to separate the small velocities produced by turbulence from the much larger signals produced by waves and currents have not existed.

Measurements aimed at quantifying the vertical transmission of drag forces by turbulence, based on state-of-the-art instrumentation and a novel technique for separating effects of turbulence from measurements dominated by waves and currents, were obtained as part of the 1997 "SandyDuck" field program, a multi-investigator, multi-institution experiment conducted in Duck, North Carolina. An array of five acoustic Doppler velocity sensors was mounted on a bottom-fixed steel frame at a water depth of 5 m. During the three-month measurement period, three instruments were damaged badly, and severe bio-fouling occurred late in the experiment. However, the remaining two sensors produced measurements sufficient to provide estimates of the force-transmitting role of turbulence during three large storms. Measurements obtained by other SandyDuck investigators provide estimates of wave and wind forcing, which are required to put the turbulence measurements in context.

The results are intriguing. The flow energetics and the relationship between the vertical structure of the alongshore current and the bottom stress indicate that turbulence generated by wave breaking did not have a large influence on the near-bottom flow. The drag force inferred from the turbulence measurements was only about half the value required to balance the wind and wave forcing. Present work focuses on understanding these results and on planning future measurements that will clarify their generality and proper interpretation.

The turbulence measurements and analysis were funded by the Mellon Foundation, the Woods Hole Oceanographic Institution's Rhinehart Coastal Research Center and the National Science Foundation. SandyDuck was funded primarily by the Office of Naval Research. Portions of this material were published in the Woods Hole Oceanographic Institution Year 2000 Annual Report.

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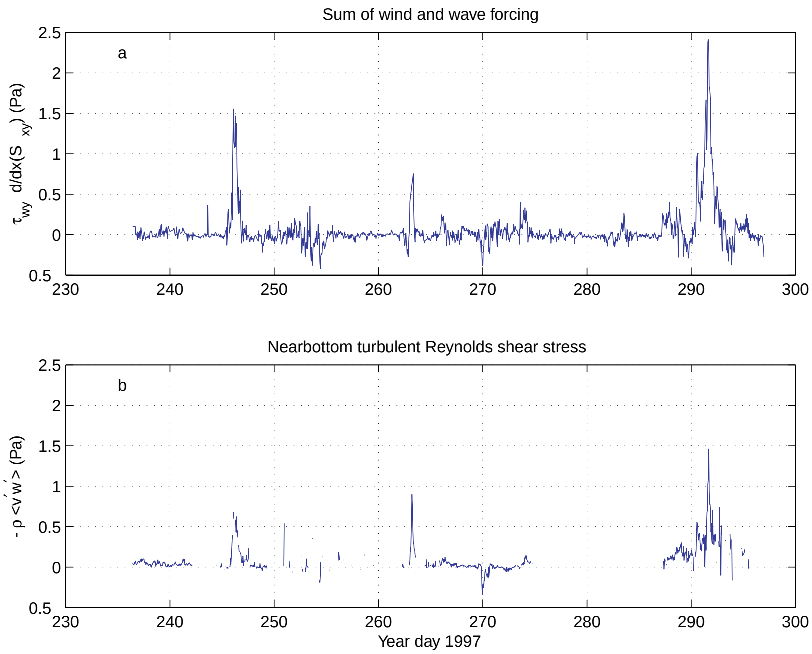


Sum of wind and wave forcing (top panel) and near-bottom stress (bottom panel) estimated from atmospheric and oceanic measurements obtained during the SandyDuck field program. Estimates of near-bottom stress have gaps because of intermittent instrument failure. According to the simplest model of wind- and wave-driven currents, the two time series should be equal. The correlation between the two time series is high (squared correlation coefficient is 0.63), but the magnitude of the near-bottom stress is too small by a factor of approximately two (regression coefficient is 0.53). J. Edson provided the wind data, and S. Elgar, T. Herbers and R. Guza provided the wave data.

- **Improved large-scale observations and models.** Because turbulence is crucial to so many large-scale processes, it is possible to use large-scale observations and models to better understand turbulence. For example, the high-quality observations from the World Ocean Circulation Experiment (WOCE) will much better define the general circulation, including thermohaline overturning, and thereby perhaps resolve the "Abyssal Recipes" paradox. Similarly, coupled with ecological and general-circulation models, satellite observations of ocean color and long-term, *in situ* observations of physical and bio-optical parameters may be expected to shed new light not only on ocean ecology but on the turbulent processes involved.
- **New ways to observe small-scale biological fields.** New optical, acoustic and chemical sensors are being developed and existing sensors are being improved and miniaturized. The combination of data from sophisticated, high-capability sensors operating from ships and remotely operated vehicles, themselves embedded in a network of data from autonomous instruments carrying robust, miniaturized sensors, opens the possibility of newly comprehensive investigations of turbulent interactions with biological systems.

WHAT IS REQUIRED FOR PROGRESS?

Open avenues toward progress in understanding ocean turbulence appear to be more evolutionary than revolutionary in all respects save one. The importance of turbulence to both the behavior of individual animals and to supporting aquatic plants dictates new collaborations between biologists and ocean physicists. This collaboration is likely to be profitable not only in the development of more comprehensive methods for field observations but also in development of ecological models and perhaps in sharing of conceptual frameworks. Equally, the broad importance of turbulence means that process-oriented students of the microscale and those investigating the large-scale consequences of turbulence need to be aware of, and keep testing, each others' perceptions. Points of disagreement, such as the "Abyssal Recipes" paradox, should be sought as quick avenues from conventional wisdom to experimental test. Debate among large-scale specialists, physical turbulence experts and biological oceanographers who manage to overcome their semantic differences will continue to be the surest way to raise these points.

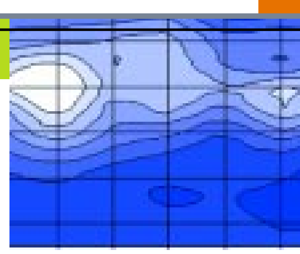
Exploitation of existing instruments and development of new and improved observational methods will likely continue to be the foundation for progress. Special mechanisms to support the frequently lengthy process of such developments will require special wisdom in the environment of peer-reviewed proposals. Hopefully it will be possible to weigh the value of sustained investment to yield new methods against the promise of immediate results using today's methods. Even with wisdom, development of new observational methods will be expensive, but past progress demonstrates the worth of this approach.

Turbulence research does not cry out for massive "organization." Progress to date has been steady and the result of numerous small breakthroughs in theory, numerical simulation and, most of all, in instrumentation and observational technique. The most productive studies have been mid-sized collaborations focused on particular regions and sets of phenomena. These collaborations have lasted only a few years and have not expended many man-years on organization or extensive programmatics. If this approach can be extended to foster collaboration among biologically and physically oriented workers, this efficient approach should serve the future well.

NON-EQUILIBRIUM ECOSYSTEM DYNAMICS

Climate properties, marine communities and entire ecosystems can all change rapidly with little warning. In some cases, the cause of change is clear. In others, the cause of change is poorly understood but may result from nonlinear responses to small perturbations that we do not perceive until they produce dramatic effects. Sometimes changes are cyclical while 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 a critical challenge that marine scientists must face during the coming decade if we are to have any hope of predicting the future state of marine ecosystems, wisely protecting and managing these ecosystems, and sustaining the many critical services that they provide.

Until recently, marine ecosystems were generally thought to be at or close to equilibrium conditions and to depart only transiently from steady state. Considerable ecological theory and empirical study has been founded on the principle that there are predictable, equilibrium states of marine ecosystems to which they will return if perturbed. Although there was an active minority arguing for the importance of chance events and historical perturbations in determining community structure, the equilibrium view shaped much of ocean ecology—small-scale experiments, large-scale descriptive studies and mathematical characterizations of key ecosystem properties in different sectors of the world ocean.



Recent studies suggest that neither physical, chemical nor biological components of marine ecosystems need to be at equilibrium. It is now recognized that many properties of marine ecosystems show directional changes over time, oscillate between different states or exhibit complex behavior as a consequence of nonlinear interactions. A related lesson from the fossil record is that long periods of little change can be punctuated by short periods of rapid change in species composition. These departures from "equilibrium" conditions are not necessarily transients from which ecosystems will quickly rebound, but may represent the more typical states experienced by most organisms in the sea. The equilibrium-based theoretical and observational tools that were commonly used in previous decades have poorly equipped the discipline to address the realities of a dynamic and changing ocean environment. Major new research efforts are needed to expand our ability to understand, model and predict the responses of marine populations and communities to these non-equilibrium conditions.

WHAT ARE THE BIG PROBLEMS?

The realization that marine ecosystems are commonly in disequilibrium presents exciting opportunities for ocean scientists from various traditional disciplines to collaborate on a spectrum of ecosystem studies. Characterization of external climate forcing which causes ecosystem variability is vital. Differentiating anthropogenic influences on marine ecosystems from naturally occurring changes is a pressing and complex challenge. Large-scale manipulative experiments are urgently needed that test hypothesized responses of communities and food webs to perturbations. Experimental investigations of the functional relationships between organisms and their four-dimensional environment are needed. New classes of models that incorporate nonlinear interactions, explicit spatial structure and non-equilibrium climate conditions need to be developed. And, an evolutionary perspective needs to be fostered that illuminates the ways in which populations and communities of organisms are adapted to the extremes, rather than the mean state of marine ecosystems.

Understanding of processes causing shifts in marine communities is inadequate, although some important factors are beginning to be identified. Some of these processes are discussed in the next section and the most promising new research directions pointed out.

Externally Forced Changes in Marine Ecosystems

Ocean ecologists are becoming increasingly aware of the linkages between external physical forcing and the responses of marine communities. Some of these physical changes are directional and progressive, with unknown consequences for the marine biota. Others appear to be cyclical, occurring across a spectrum of temporal frequencies. Still others are episodic, with no predictable recurrence interval but having the potential to greatly influence the structure and function of marine communities. Whether directional, cyclical or episodic, understanding the consequences of such changes in the external environment for marine communities is an exciting and open field ripe for new forms of scientific collaboration and innovative investigation.

Secular changes. Other than the direct effects of human interference, such as overfishing and habitat modification, the most conspicuous directional changes in the atmosphere and upper ocean in the twentieth century are the progressive increases in CO_2 , CH_4 and other radiatively active gases. The capacity of the ocean to assimilate these gases, the consequences for the ocean's chemistry and the role of the biological pump in modifying atmospheric gas content and heat flux to Earth's surface are subjects of active investigation. The consequences of these secular changes for the ocean's biota and the role of the ocean's biota in influencing the atmosphere are major problems that have only begun to be addressed.

While some studies have documented significant warming of the upper ocean in the last 40 to 50 years, it is not yet clear whether these changes should be considered secular trends or part of a long-term, cyclical oscillation of unknown periodicity. In any case, warming of the upper ocean has, in some regions, led to increased vertical stratification that can have significant consequences for the vertical diffusion of nutrients and for primary and secondary production. In tropical oceans, an increase in the duration of annual extreme high temperatures have been associated with widespread coral bleaching and death. In the Antarctic, reduced winter sea ice coverage appears to be changing the types of grazers in pelagic food webs, which in turn alters the biological pump exporting carbon to the seafloor (see Antarctic Marine Ecosystem box on page 74). Documenting such trends, and discerning the mechanisms through which they influence oceanic communities, is a important direction for the future.

The long-term, 70% decline in the total biomass of zooplankton of the California Current system between the 1950s and the 1990s is another example of a change that has been interpreted as part of a cyclical phenomenon (see "Interdecadal scale changes" below), but the instrumental record is too short to differentiate clearly between long-term, periodic behavior and a secular trend. The flux of organic matter to the deep-sea benthos has also declined in the last decade, concomitantly with the decrease in zooplankton in overlying surface waters. Hence, perturbations in the atmosphere may influence upper ocean plankton communities and propagate through a 4000 m water column to the deep seafloor. Rising ocean temperatures have also been associated with geographic alterations of species' distributions. Along the US coastline, southern fishes and intertidal organisms have both expanded northward. Detecting and understanding these perturbations and community alterations represent exciting new opportunities.

Other secular trends, such as the increase in the intensity of the ozone hole and consequent changes in uv-b flux, have already been found to influence photosynthetic activity of marine phytoplankton and developmental processes in larval marine invertebrates. The longer term consequences of such changes at the population and community level are unknown.

A long-term trend toward increased nutrient influx into the coastal Gulf of Mexico may be increasing the frequency of hypoxic events on the continental shelf. However, the increased flux of nutrients into these oligotrophic waters an have two markedly different fates. The new nutrients may stimulate primary and secondary production in the water column, which can ultimately enhance fish production. Alternatively, the enhanced primary production may flocculate as unutilized organic matter on the continental shelf where its oxidation results in severe oxygen depletion in the water column that can kill fishes. It is not well understood how these markedly different pathways are controlled.

Decadal Scale Changes in the Antarctic Marine Ecosystem

Contributed by Valerie Loeb, Moss Landing Marine Laboratories
William Fraser, Montana State University
Roger Hewitt, Southwest Fisheries Science Center

Antarctic krill, *Euphausia superba,* is the major food source for higher-level predators including penguins, fish, seals and whales and is considered the keystone species of the Antarctic marine ecosystem. Another pelagic animal, the gelatinous tunicate *Salpa thompsoni,* can also be abundant in the Antarctic Peninsula area during spring and summer months. Salps constantly filter seawater, ingest phytoplankton and small zooplankton and produce dense fecal pellets as they swim through the upper water column. During episodic and massive spring-summer blooms, salps can have a major impact on other zooplankton through competition for planktonic food particles and predation upon small organisms such as krill eggs and larvae. Unlike krill, salps have relatively few predators and most of the newly fixed carbon ingested by salps in the upper water column is lost to deep waters via downward transport of fecal pellets. Hence, whether krill or salps predominate in the upper water column has significant implications for the functioning of the Antarctic ecosystem.

Between-year variations in krill and salp abundance have been related to winter sea ice development (Loeb et al., 1997). Two successive winters of strong sea ice development appear to favor low salp abundance, good krill reproductive success and substantial krill population growth, while relatively low winter sea ice extent is associated with poor krill recruitment success and massive summertime salp blooms. The positive relationship between krill recruitment and winter sea ice development is believed to be due to the ability of krill to feed on abundant ice algae and other food growing under sea ice, as well as the refuge from predators provided by cracks and crevices within the sea ice. Low salp competition and predation pressure during these periods are hypothesized to enhance krill recruitment success. In contrast, rapid salp population increases are thought to occur in open water during years when phytoplankton growth in early spring is not limited by sea ice cover.

Long-term, interdecadal shifts in abundance of krill (Figure), krill predators and salps have been related to the decreased frequency of winters with extensive sea ice development, which are in turn associated with a warming trend observed in the Antarctic Peninsula area since the 1940's (Fraser et al., 1992; Loeb et al., 1997). The frequency of cold winters with extensive sea ice cover has decreased from every four out of five years during the middle of the last century to only one or two out of five years since the 1970's.

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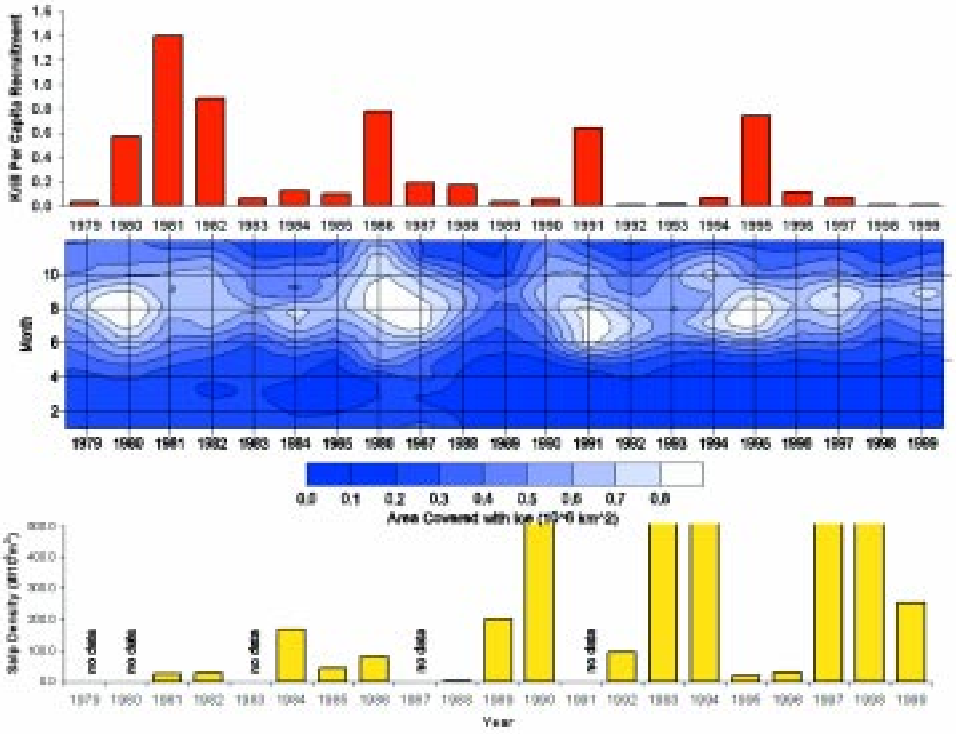


Cyclical changes in climate. In the 1990s our awareness increased of the presence of interannual and longer-period variations in the atmosphere and ocean in virtually all ocean basins. In a limited number of instances there is already clear evidence that marine populations respond in dramatic ways to these variations (e.g., "regime shifts" in the North Pacific and plankton responses to the North Atlantic Oscillation). In other instances there is suggestive evidence that some of the long-period variability in marine communities may be directly influenced by cyclical climate variations. There are now significant opportunities to understand the mechanisms linking climate with fluctuations in marine populations and communities.

Interdecadal scale changes. Recent observations from the North Atlantic and North Pacific suggest that there are remarkable decadal-scale climate oscillations linked to the variability of marine populations (see Pacifical Decadal Oscillation box on page 22). It seems likely that such linkages will also appear in other ocean basins (see Global Climate chapter). While the precise mechanisms involved and the timing of the transitions between ecosystem states are not yet clear, there is evidence that some populations in major marine ecosystems oscillate between different states in phase with large-scale forcing from the atmosphere and upper ocean. In some cases there are relatively rapid changes from one dominant mode to another. These results have broad implications for the way we study and manage marine ecosystems. The possibility that the ecosystem is currently not at equilibrium and may change relatively quickly to a new state means that scientists and resource managers must pay close attention to the state of the climate cycle as well as to present-day conditions. Ill-timed exploitation of a marine population during a period of natural decline can severely depress a marine resource for decades. There could be similar consequences if pathogens, hurricanes or other perturbations negatively impact populations during these critical periods. This underscores the need to understand the longer-period climate properties and the ways in which climate cycles interact with other important processes affecting marine populations.

Interannual changes. The El Niño-Southern Oscillation (ENSO) is the largest known short-term climate signal in the world ocean (see ENSO box on page 40). Large El Niños in the twentieth century have resulted in major declines in fishery harvests (finfish, sea urchins, squid), severely altered kelp forests, depressed biomass of zooplankton, temporarily displaced lower latitude organisms into high latitudes, exacerbated coral bleaching and reef loss, and increased rates of parasitic infection of some marine organisms. The new ability to project the occurrence of El Niños has benefited the design of experimental and observational programs (and permitted human agencies to prepare for the environmental and social consequences of the event). Despite this new ability to forecast, there is still uncertainty as to how the tropical perturbations are propagated into high latitudes: to what extent does the signal propagate through the ocean and to what extent through the atmosphere? In the future, improved understanding of physical propagation mechanisms and biological responses should permit the forecasting of El Niño effects on ocean populations in a way that can be used for the adaptive management of marine resources.

Other interannual perturbations, such as variations in the ocean's thermohaline circulation, may result in changes in stability of the Southern Ocean as a consequence of increased freshwater input. The consequences of such changes for ecosystems and for world climate have not been adequately explored.

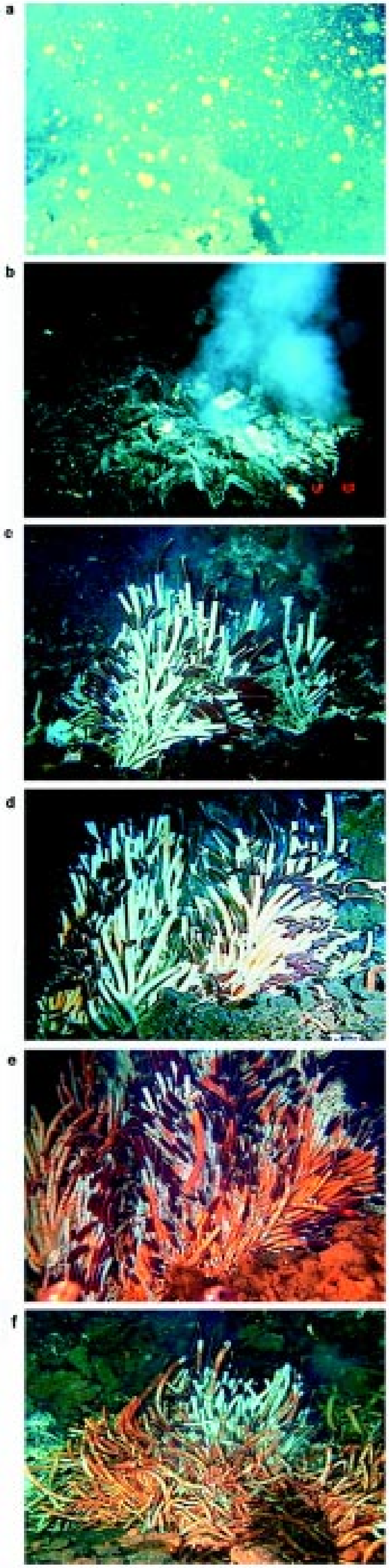


Figure 11. Temporal sequence of faunal community development near a primary eruptive fissure at 9° 50'N along the East Pacific Rise following a volcanic eruption in 1991 (see Figure 18 on page 115 in the Ocean Below the Seafloor chapter for vent chemistry and temperature sequence in same vent area). The photos were taken from *Alvin*, and all are of the same view. (a) April 1991: no vent megafaunal organisms present when vigorous hydrothermal circulation was initiated, but profuse microbial material was being expelled. (b) By March 1992, the fissure was colonized by an extensive population of *Tevnia jerichonana*, with *Riftia pachyptila* noticeably absent. (c) By December 1993, numerous *R. pachyptila* had settled and rapidly grown to form a dense thicket, engulfing the existing *T. jerichonana*. (d) Between December 1993 and October 1994, continued rapid colonization and growth by large numbers of *R. pachyptila* dramatically increased the density, lateral extent and vertical growth within this colony. (e) By November 1995, the density and lateral extent of the colony continued to increase. The colony was now occupied by over ~2000 *R. pachyptila*. About half of the *T. jerichonana* assemblage documented in 1992 was alive in 1995 at the base of the *R. pachyptila* tubes. The staining of worm tubes with a rust-colored ferrous-oxide precipitate was coincident with increased concentrations of iron in the diffuse vent fluids (maximum recorded was 33°C), and a decrease in H_2S, supporting this colony. (f) By November 1997, although the temperature of the fluids remained high (27.2°C), almost no H_2S remained in the fluids, and the *R. pachyptila* community had noticeably declined. Reprinted from *Deep Sea Res. II*, **45,** Shank, T.M., D.J. Fornari, K.L. Von Damm, M.D. Lilley, R.M. Haymon and R.A. Lutz, Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents along the East Pacific Rise, 465-515, copyright 1998, with permission from Elsevier Science. The figure, which has been modified from the original to include Frame (f) (unpublished data), was supplied by Tim Shank, Woods Hole Oceanographic Institution; Richard Lutz, Rutgers University; and Karen Von Damm, University of New Hampshire.

Episodic changes. A variety of episodic changes occur in marine ecosystems and may perturb communities and ecosystems away from equilibria, or may introduce new conditions which can transiently favor entirely new communities. Some examples include the relatively sudden birth and death of hydrothermal vents (Figure 11). The emergence of vent fluids is followed by rapid colonization and proliferation of vent-adapted organisms, then their local demise when the hydrothermal fluids exit elsewhere in Earth's crust. Hurricanes have been found to result in a wholesale decimation of coral reef communities, although some corals show remarkable resilience to such changes. Some anthropogenic influences such as oil spills can be extreme perturbations to ecological systems, whose recovery potential is poorly understood.

Internally Driven Changes in Marine Systems

In addition to perturbations to marine communities caused by external physical factors and by humans, numerous processes internal to populations and communities can cause relatively abrupt shifts in the composition and function of the ocean's biota. Understanding these processes, which often develop from nonlinearities in the interactions between individuals within a population, or between species, is an important challenge in the ocean sciences.

Trophic Cascades. In addition to strong direct effects on prey, consumers can have pervasive, indirect impacts on community organization when the prey are themselves strong interactors with other species in the community. These indirect effects can extend well beyond the particular prey taxa consumed. Such indirect interaction chains can produce trophic cascades, in which the impact of an apex predator cascades through the intervening trophic levels to influence the abundance of primary producers and the organization and composition of the community in general.

The trophic cascade concept is best exemplified by long-term studies of the interactions of piscivorous fish, planktivorous fish, zooplankton and phytoplankton in North American lakes. In these systems, both observational and experimental studies indicated that all lower trophic levels could be altered dramatically by changing the density of top consumers. Similar cascades occur in the marine realm. Interactions among sea otters, herbivorous sea urchins, and kelps provide a dramatic example. In areas occupied by sea otters, herbivorous sea urchins are rare, kelps are common, and the large numbers of fishes and other species that recruit to kelp beds produce a system that is highly productive, rich in biodiversity, and important for exporting energy to surrounding communities. When sea otters are absent, urchins overgraze the kelps, the biogenic structure that defines the system is lost, and the system consists of high densities of urchins, a few encrusting seaweeds that are resistant to grazing, and little else. Thus, in the absence of sea otters, species-rich kelp beds can change to species poor urchin-barrens. Such shifts have occurred after fur traders drove the otters to near extinction and after killer whales along the coast of Alaska switched from their normal prey to feeding on sea otters. Once urchin barrens have been established, they can persist for long periods in the absence of sea otters, but if otters are reintroduced to the area, they rapidly consume the urchins and promote reestablishment of kelp bed communities.

In pelagic marine systems there are several patterns suggesting that trophic cascades allow perturbations of upper trophic levels to cascade down and influence phytoplankton dynamics in the open ocean. In the subarctic Pacific between 1990 and 1994, surface chlorophyll and salmon abundance alternated synchronously between high values in odd years and low values in even years, while zooplankton biomass varied with an opposite sign, i.e., low in odd and high in even years. A likely explanation for this interannual oscillation involves the releases of hatchery-reared salmon and their predatory impact on herbivorous zooplankton; by depressing zooplankton, salmon appear to release phytoplankton from grazing pressure. The potentially complex nature of these interactions illustrates the need for cooperative, multifaceted research programs.

Other Nonlinearities. Existing classical, linear models of food webs have long predicted that complex communities are inherently unstable. Such models predict that the presence of large numbers of interacting species will tend to cause large fluctuations in abundances of other organisms and thus to destabilize food webs. However, a recent model that allows communities to display nonlinear trophic interactions and to display nonequilibrium dynamics arrives at the opposite conclusion: large numbers of weak interactions between species tend to dampen oscillations and thus to stabilize communities (see Biodiversity and Ecosystem Stability box on page 78). This new result agrees with abundant evidence for large numbers of interacting species found in nature.

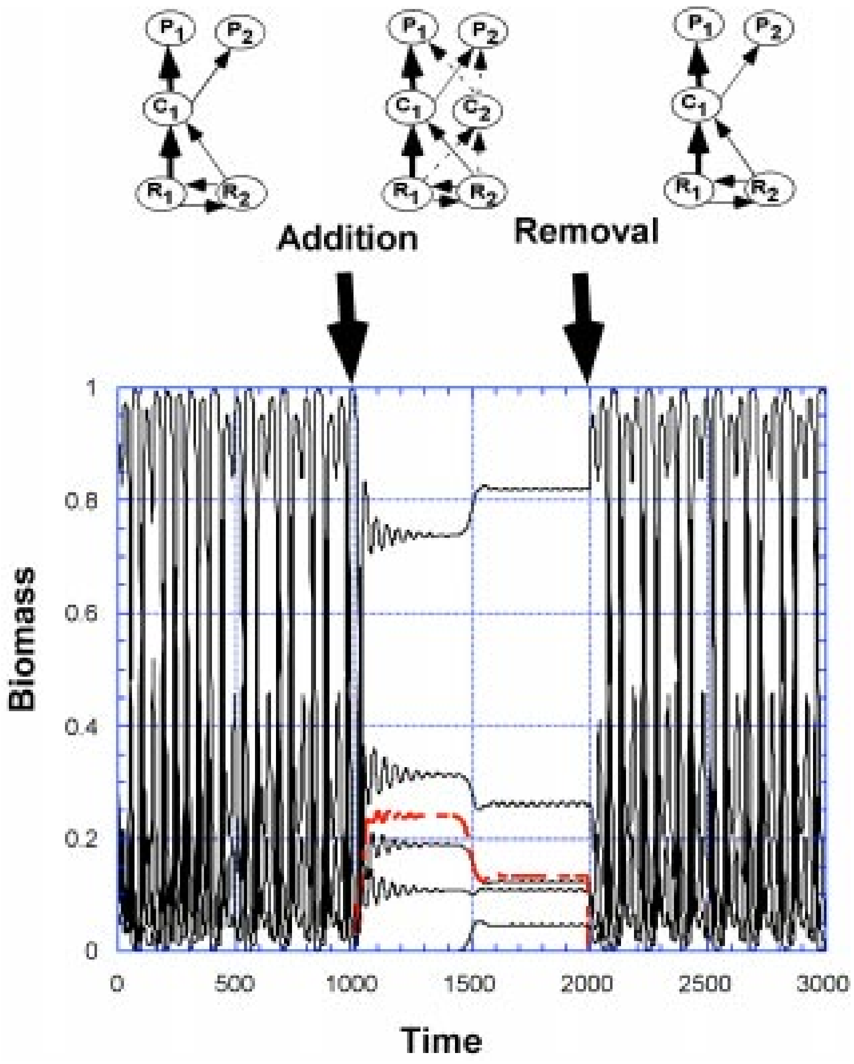
Biodiversity and Ecosystem Stability

Finding Strength in Weakness

Contributed by Kevin McCann, McGill University, Canada

There is little doubt that Earth's biodiversity is declining. The problem forces us to consider how we expect ecosystems to respond to reduced biodiversity. Will they collapse upon reaching a threshold of diminishing biodiversity? Or will they remain stable and function efficiently, continuing to sustain key fish and other populations and to modulate geochemical cycles? Prior to 1970, ecologists believed that ecosystem stability and function depended on diversity. However, these notions were challenged in the 1970s by theoretical ecologists who showed, using mathematical models under equilibrium assumptions, that diversity in and of itself tended to destabilize ecosystems. The results puzzled ecologists as real ecological communities are interconnected assemblages of large numbers species, but the mathematical theory seemed unassailable.

Recently, using food web models where parameters are estimated from empirical relationships between body-size and physiological rates (e.g., metabolic rates, consumption rates), ecologists reinvestigated this result under a less restrictive non-equilibrium definition of stability. By defining stability from a non-equilibrium perspective (e.g., more stable communities are those that have population densities further bounded away from near-extinction densities), ecologists have begun to find that a number of common food web interactions between species (e.g., omnivory, generalist predation) lead to more, rather than less, stable ecological communities. This result has one major condition: it requires that weak consumer-resource interactions (i.e., food web interactions where a consumer has little impact on its prey) dominate the distribution of food web interactions in real communities. Following this logic, as long as weak interactions accompany large food webs of many interacting species, then diversity should generally correlate positively with stability. The figure shows one simplified model simulation with the addition and subsequent removal of a weakly interactive species (C_2). The weak interactor inhibits the destabilizing role of several strong consumer-resource interactions, which by themselves generate large oscillations in species abundances. Without the weak interaction, the system is threatened with collapse (Figure). Note that redundancy in the number of weak interactors further enhances community stability, ensuring that communities dominated by weak interactors lead to greater ecosystem stability. Preliminary data on the distribution of interaction strengths in natural communities are consistent with this view, such that the distributions of interaction strength are skewed towards a majority of weak interactions in natural food webs.



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Time series for a simple food web model with the addition of a weakly interactive species, C_2, at time 1000, and removal at time 2000. Corresponding food web diagrams are shown throughout the run.

Other recent studies have highlighted some additional nonlinearities in the interactions between organisms that cause pronounced changes in community patterns and the state of marine ecosystems. These include disease, mating failures or interactions of these factors. For organisms that fertilize their eggs externally, such as abalone or sea urchins, reproductive success is facilitated where adults are present in high densities so that sperm and eggs released into the water column have high probabilities of contact soon after release. When adult densities are lower, field measurements have shown that few eggs are successfully fertilized. It thus appears that localized, high-density patches of animals may be a critical aspect of successful reproduction for these species. Unfortunately, the high densities that facilitate fertilization also may promote increased susceptibility to disease transmission. Both the Caribbean sea urchin *Diadema antillarum* and the black abalone in the Northeast Pacific have experienced dramatic mortality due to diseases that spread rapidly throughout the entire population and apparently reduced population densities below a threshold needed for successful reproduction. Closer analysis of such nonlinear interactions will lead to much greater predictive ability in the future.

Harmful Algal Blooms. Of approximately 5,000 species of marine phytoplankton, some 300 species form blooms that can discolor the sea surface (so-called "red tides"), with about 40 of these species also producing potent toxins that affect community structure, ecosystem function, fisheries and even human health. Although blooms are natural phenomena that have occurred throughout recorded history, there is accumulating evidence that harmful algal blooms have increased in intensity, frequency and geographic extent since the 1970s. Factors promoting increased blooms are debated, but include ballast water introduction of exotic species into new areas, coastal eutrophication and climate change. The paralytic shellfish toxins acquired by shellfish through ingestion of dinoflagellates also could have large-scale, cascading effects on community structure through their indirect effects on keystone species such as sea otters or other predators.

Regardless of the causes of blooms, the chemically mediated and ecosystem-wide effects of toxic phytoplankton blooms can be dramatic, including large scale die-offs of scallops, fishes, birds, marine mammals and other organisms, and the resulting loss of hundreds of millions of dollars in fisheries and tourism revenues. Along the US Gulf Coast, outbreaks of the toxic dinoflagellate *Ptychodiscus brevis* have been estimated to kill up to 100 tons of fish per day, and similar effects of dinoflagellate blooms have occurred in many parts of the coastal ocean.

Determining the mechanisms leading to such blooms, the causes for changes in their frequency of occurrence, and developing potential control mechanisms is a significant problem for the coming decade.

Invasions

The study of the dramatic and unexpected effects of the introduction of exotic species into local marine waters represents a newer field of marine ecology—the science of invasions. There are now numerous examples of how these invasive organisms have altered local aquatic communities, from the change in whole estuarine areas (e.g., San Francisco Bay), to alterations of water quality in the Great Lakes by the introduction of the zebra mussel, to problems with specific taxa in the coastal ocean (e.g., the introduction of a worm endemic to South Africa into California waters, which hinders shell growth in abalone).

Catastrophic Decline of the Jamaican Coral Reef

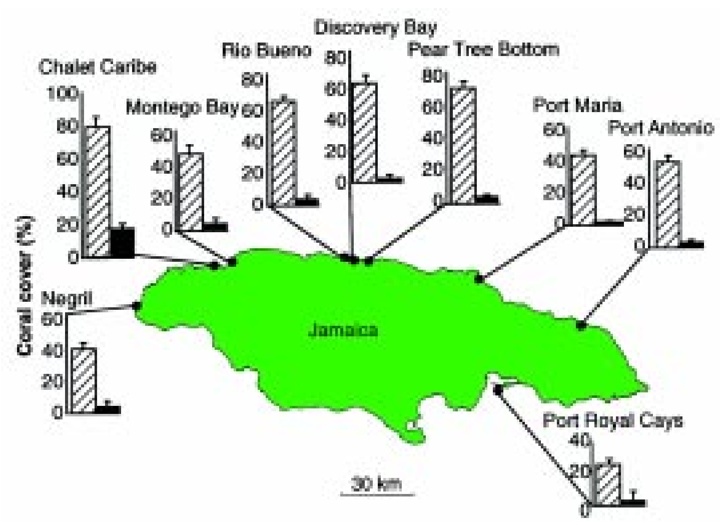
Contributed by Terry Hughes, James Cook University, Australia

Caribbean coral reefs provide an example of nonlinear and large-scale community shifts that appear to result from multiple interacting stresses that are largely anthropogenic and that have fundamentally changed these diverse ecosystems over the last two decades. The speed and extent of change, and the urgency of the need for understanding and addressing these changes, is best documented for reefs in Jamaica, where live coral cover declined from more than 50% in the late 1970s to less than 5% by the early 1990s.

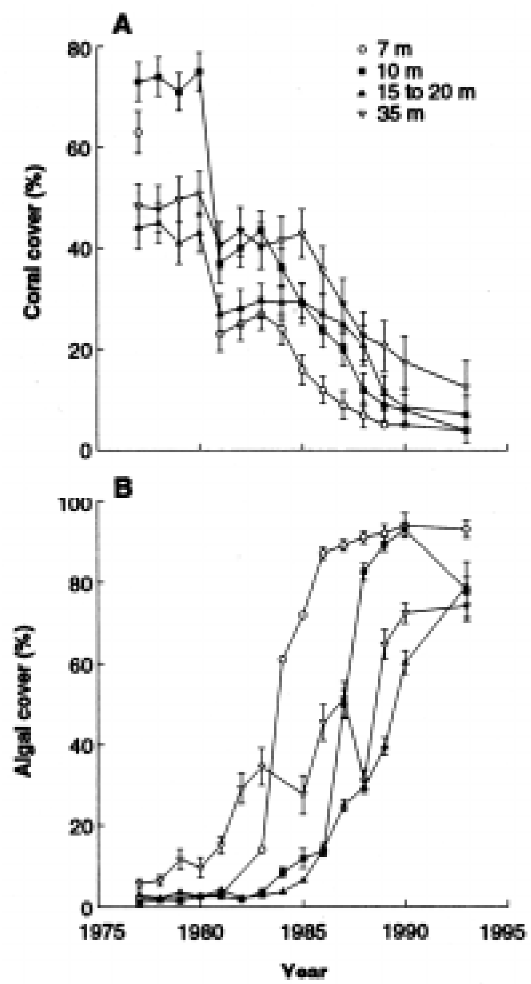
Jamaica is the third largest island in the Caribbean and is the center of coral diversity in the Atlantic Ocean. Jamaica's human population has undergone exponential growth and by the 1960s, fishing pressure was estimated to be two to three times above sustainable levels. Although fishing pressure had been high for an extended period, and herbivorous fishes that remove seaweeds (preventing them from overgrowing and killing coral) had been severely reduced, the reefs had not shown signs of change due to overfishing. In part, this resulted from an ecological replacement of fish grazing by a dense buildup of the herbivorous sea urchin *Diadema antillarum*. High densities of this sea urchin are correlated with fishing pressure, which removes fishes that both prey on and compete with the urchin. In the early 1980s, *Diadema* near the Caribbean opening to the Panama Canal began to die due to a species-specific pathogen. Within a year, this disease spread throughout the entire Caribbean and caused 95-99% mortality in *Diadema* densities Caribbean-wide. With *Diadema* removed by the pathogen, and herbivorous fishes continuing to be removed by fishing, reefs around this entire island nation underwent a spectacular change in community structure that has persisted from the early 1980s until today. Between 1977 and 1994, coral cover declined from 52% to 3% and seaweed cover increased from 4% to 92% along the more than 300 km of coastline that was monitored (Figure left). This pattern was also apparent at all depths surveyed (Figure right). Species-rich and topographically-rich coral reefs have been replaced by topographically simple algal beds that do not attract or support large numbers of other species.

The high seaweed cover preempted space and virtually stopped coral recruitment (a process that is necessary for coral recovery). The few remaining sea urchins now had an overabundance of algal food; they grew rapidly and put more energy into reproduction, but there has been minimal recruitment of *Diadema* onto the reef. As external fertilizers, their spawning success is strongly density dependent (i.e., if they are not crowded to the point of it stunting their growth, then there is much lower probability of sperm contacting eggs when they are released into the water column). Densities may be too low for successful spawning.

Although coral reefs have flourished through major fluctuations in sea level occurring over scales of 10^3 to 10^5 years, reefs around Jamaica changed dramatically, and with no warning, in about 10 years. There have been no significant signs of recovery since that time. Given the life span and size of corals that comprise the significant frame builders on these reefs, recovery may take decades to hundreds of years, if it occurs at all.



Large-scale changes in community structure at fore-reef sites along >300 km of the Jamaican coastline, surveyed in the late 1970s (1977, hatched bars) and the early 1990s (1993, solid bars). Figures (left and right) reprinted with permission from Hughes, T.P., Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef, *Science*, **265**,1547-1551, 1994. Copyright 1994 American Association for the Advancement of Science.



Degradation of Jamaican coral reefs over the past two decades. Small-scale changes in (A) coral cover and in (B) macroalgal cover over time at four depths near Discover Bay.

The characteristics that make particular species efficient invaders, and the properties of assemblages that make them less or more susceptible to invasion, require greatly expanded study in the future. As with many other topical issues, our future ability to address these problems will depend greatly on reinvigorating the field of systematics. Taxonomic expertise is vital to correctly identify and distinguish exotic and native species, and to understand their modern day ecology and biogeography.

Pathogens and Parasites

Just as predators can affect the structure of marine communities, pathogens and parasites can cause dramatic and long-term changes in marine ecosystems. This topic is mentioned separately because not only is it poorly understood, but it is potentially of great significance to ecosystem dynamics. Marine scientists have recently drawn attention to the role of both climate variability and human activity in increasing the incidence of outbreaks of waterborne diseases. Some pathogens are known to adversely affect marine shellfish, echinoderms, corals and mammals. Others, such as the cholera-inducing marine *Vibrio* bacteria may attach to the chitinous exoskeleton of zooplankton such as copepods, which act as vectors for the dispersal of this human pathogen.

In addition to this indirect effect of a pathogen on marine community structure, pathogens also appear to be having considerable direct effects via diseases of corals, sponges, gorgonians, seagrasses and other organisms that produce the basic biogenic structure of marine ecosystems. In the 1930s, eelgrass along the American Atlantic coast was devastated by disease, as were tropical sponges in numerous areas of the Caribbean. Caribbean corals have declined throughout the entire region. In some areas, the coral decline resulted from the indirect effects of a pathogen that killed sea urchins which in turn were preventing corals from being overgrown by seaweeds (see Jamaican Coral Reef box on page 80), but for other areas the causes for decline were less clear. Given that these corals provide the biogenic structure and habitat complexity upon which many other reef organisms depend, the indirect effects of coral loss on biodiversity and community structure are considerable. Even our very inadequate knowledge of diseases in the marine biota is largely limited to those cases where the impact is close to catastrophic. An opportunity exists to greatly increase our knowledge of pathogens in the ocean, their effects on populations, communities and ecosystems, and on how the biota naturally defend against them.

Metapopulation Dynamics

Marine populations are frequently structured into semi-isolated subunits. These geographically distributed subpopulations are linked to one another through advection and diffusion, as well as through active behavioral migration. Exchanges can involve individuals of any age, but often involve transport of early stages in the life history (i.e., larval, spore and early juvenile stages). Ignorance of movement during these stages is a major impediment to understanding the population dynamics of marine organisms. These linkages between subpopulations play a defining role in local and metapopulation dynamics, community interactions, evolutionary dynamics and the management of marine populations and reserves. Scales and intensities of subpopulation linkages depend on life-history characteristics (e.g., reproductive mode and larval stage duration), physical forcing (advection and diffusion) and organismal behavior (e.g., diel vertical migration and responses to chemical cues). Over the last two decades, it has become clear that some of these processes affect the rates and scales of dispersal, but there is no comprehensive understanding of population linkages for any marine system.

Traditionally it is assumed that dispersal magnitude and gene flow are proportional to the length of time a propagule spends in the plankton, but this simple approach is inadequate. Observations of meroplanktonic stages that can spend weeks to months in the water column provide conflicting evidence about scales of dispersal. Some observations, such as the rate of spread of invasive species and the presence of larvae at great distances from their parental ranges suggest that the scale of dispersal can be hundreds to thousands of kilometers. Other observations suggest that the actual scale of dispersal is substantially lower (< 10 km). For example, there can be considerable genetic heterogeneity over short distances in continuously distributed species, and there is temporal variation in the genetic composition of recruits. Equally disconcerting is the realization that species without a planktonic dispersal phase can fail to show genetic differentiation across large spatial scales. One cannot hope to understand biogeochemical processes, the effects of changing climate on marine ecosystems, or to predict the effects of anthropogenic stresses without improved evolutionary understanding of marine population linkages.

Resolving the problem of unknown population linkages will require quantifying the temporal and spatial variability of dispersal paths, and the consequences of dispersal for population and evolutionary dynamics. These studies initially should focus on larval or spore transport. Rapid progress depends on identifying tractable field systems. Ecosystems with spatially discrete populations, such as island chains, estuaries, hydrothermal vents or systems with sharp boundaries between distinct circulation regimes (e.g., at prominent biogeographic boundaries such as Cape Hatteras or Point Conception) represent especially productive research opportunities.

WHAT MAKES PROGRESS POSSIBLE NOW?

- **Coupled physical-biological observational programs.** New opportunities exist for physical scientists and ecologists to collaborate in studies of the responses of marine ecosystems to variations in atmospheric and oceanic forcing. . Recent advances in continuously measuring observational platforms deployed in environments from the intertidal to the deep sea have set the stage for cooperative research programs. Platforms range from space- and aircraft-based remote sensors, moored arrays and seafloor observatories, to remotely operated vehicles and free-drifting autonomous vehicles and surface-based vessels. The development of new sensors now permits remote assessment of fine-scale turbulence, as well as the optical and acoustic measurement of different varieties of plankton and marine snow. Developments in molecular genetics holds the promise for much more rapid, automated identification and enumeration of marine organisms. Such observational programs need to be synchronized so that the sampling scales for the atmospheric, oceanic, and biotic properties of marine ecosystems are compatible. The realization that secular and cyclical changes in the physical and chemical environment impose a non-steady state driver on biological systems opens new doors to research programs in which the ocean sciences are better linked.

- **Convergence of ecological and paleoceanographic measurement scales.** Ecologists have begun to resolve biological changes on time scales longer than those traditionally studied, while geologists and paleoceanographers are concurrently developing the ability to resolve changes on shorter time scales. Such convergence of time scales presents opportunities to extend contemporary ecological understanding into the geological past. For example, the ability to resolve annual variations in population size of pelagic fishes from varved sediments, to infer the population size of Pacific salmon from the stable nitrogen isotope signature that they deposit in lake sediments after spawning, or to resolve annual variations in marine climate from coral records, means that ocean scientists have new opportunities to directly link the extant processes observable today with those affecting marine communities in the geological past. In some instances, sufficiently long time series of organismal abundances or proxy variables overlap the time period of the instrumented measurements within the twentieth century, thus permitting the sedimentary record to be validated and more reliably extended into the past.

  Many of the proxy measurements upon which paleoclimate reconstructions are based are founded on inadequate knowledge of the ecology of the organisms involved and rest on assumptions that have been poorly validated. The habitats occupied by organisms, processes regulating the mineralization of skeletal hard parts, and physiological changes that induce different vital effects across the life history of organisms require careful attention in order to more accurately characterize ecosystem change. Partnerships among biologists, chemists and geochemists would be highly beneficial in this area.

- **Modeling.** New ocean-atmosphere circulation models are now being coupled with ecological process models. Diagnostic numerical models can be used to test understanding of marine ecosystem responses to perturbations. Fully developed four-dimensional circulation models can be coupled with simulations of marine organism population dynamics. The appropriate scales for such models is a recurrent issue because larger-scale processes invariably influence (and sometimes dominate) the local scales. Models on nested scales are often required. In another class of ecosystem model, we are on the cusp of entering a new phase in ecological studies—ecosystem forecasting. In a few selected marine ecosystems where there are appropriate, long-standing observational programs, we are beginning to test knowledge of the system through the development of forecast models. Such models will be prognostic and forward-projecting and will be regularly updated by observational programs. Short-term predictions will be regularly adjusted through assimilation of data. By analogy with the development of forecasting methods in meteorology, this process is expected to evolve rapidly in the coming years and decades.

- **Large-scale ecosystem manipulations.** Marine ecosystem studies entered a new era with the successful IronEx experiments (see IronEx box on page 31). Although pelagic systems have been manipulated in enclosed water columns for decades and localized manipulations of benthic communities have been a research tool for scientific generations, IronEx heralded a new ability to manipulate an unencumbered water column in the open ocean and to measure both biological and geochemical consequences. Such bold manipulative experiments provide critical tests of ecosystem function. This approach could profitably be extended into many areas of ecosystem research. Do pink salmon releases truly induce trophic cascades in pelagic ecosystems? Controlled releases of these predators from selected hatcheries could test the validity of the hypothesis. Is local persistence of estuarine populations of bivalves critically dependent upon exchange of organisms (and genetic diversity) with other subpopulations? Temporary isolation of estuarine populations could help answer the question. Can the invasiveness of different taxa be predicted (and controlled)? Judicious manipulations of hypothesized biological control agents in semi-isolated environments could test the viability of the hypothesis.

WHAT IS REQUIRED FOR PROGRESS?

- **Integrated, long-term measurement programs.** Measurement programs that extend over larger space and longer time scales than have typically been pursued are urgently needed. For climate-related studies, biotic variables need to be measured on sufficiently large scales to integrate the larger-amplitude environmental signals and be compatible with the measurement scale of the physical properties. Concurrent process-oriented research programs and manipulative experiments are needed to test the mechanisms thought to link the larger-scale forcing to population and community variations.

  For studies oriented more toward episodic or event-scale processes, measurement techniques are needed that permit the occasional rare event to be captured and fully resolved because of the sensitivity of many nonlinear interactions to these extremes. Averaging measurement techniques are often criticized because such measurements can underestimate rate processes in biological "hot spots"—for example, microassemblages of heterotrophic bacteria on particles or around organic aggregates, or the accumulation of planktonic organisms in vertical thin layers in the water column. The degree to which biological and chemical rate process are regulated by such high-density assemblages needs to be resolved, as does the biological composition of such hot spots and their temporal duration. New measurement technologies that permit unattended assessment of organismal abundances, growth rates, behavior and spatial patterns, concurrently with characterization of the physical environment, are greatly needed. Autonomous instruments, remotely operated instruments and space-based remote sensing technologies should be expanded and more fully utilized. The biotechnology revolution should be more fully exploited in the development of new measurement techniques and approaches.

- **New model development.** There are opportunities for development of several classes of ecological models. Spatially explicit models are needed to predict dispersal pathways, connectivity of subpopulations, variations in abundance and the persistence time of marine populations. Knowledge of the interactions of animal behavior with flow fields will be required to build realistic simulations of metapopulation dynamics.

  Because model projections tend to quickly outstrip the data available, coordinated development of research teams of modelers, observationalists and experimentalists will ensure that there is rapid communication about the most important measurements and processes. New experimental and observational studies can then be focused on the processes to which ecosystem states are found to be most sensitive.

Expanded efforts in the training of graduate students and retraining of more advanced scientists are urgently needed to help develop these new integrative models. Many require new partnerships of ecologists with physical scientists, modelers or applied mathematicians. Thus, there is a need to accelerate the development of scientists with the skills and knowledge to work across traditional boundaries. This will produce an ever-increasing need for deeper quantitative training of biologists, but also a parallel need for graduate students and researchers in physical oceanography, chemistry, and other disciplines to become better acquainted with the important problems and processes in ocean ecology.

- **Taxonomic underpinnings.** The fundamental biological unit in marine ecosystems is species. Most of the future of ecosystem research rests upon knowledge of the component species, their diverse identities, life history characteristics and roles in geochemical transformations and other ecosystem functions. Yet, paradoxically, at a time when this information is most needed, it is least available. In many different scientific forums, the dearth of taxonomists and restricted pipeline of young talent in the field of systematics have been discussed. A National Academy of Sciences workshop on Marine Biodiversity pointed to a critical need for the support of taxonomists, their incorporation directly into field and experimental research programs and the training of a new generation equipped with appropriate new analytical and numerical techniques. Apart from the nascent Census of Marine Life, no significant action has been taken to improve the situation in marine systematics, and meanwhile the problem has only intensified. Major scientific issues ranging from paleoclimate reconstructions using marine microfossils, to understanding the agents responsible for harmful algal blooms, to understanding global patterns of the ocean's biodiversity cannot be resolved unless the taxonomic underpinnings of marine research are supported and reinvigorated.

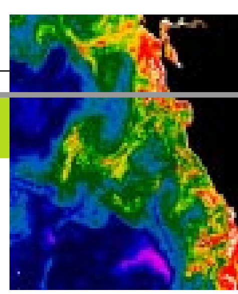
- **Longer duration of research grants.** New appreciation of the dynamic nature of marine ecosystems, and the different characteristic modes that ecosystems may exhibit, requires a longer-term research perspective than has been customary in NSF ocean sciences-funded studies. The traditional three-year grant is not sufficient to characterize or understand the important processes controlling ecosystem dynamics. Studies of longer duration are much more likely to achieve a deeper understanding of the variable states of natural ecosystems and the mechanisms leading to transitions between states. Although we actively encourage NSF to continue funding new ideas that might be profitably tested on a shorter time frame, there is a compelling need to fund innovative ecosystem science on a sufficiently long time frame to understand the mechanisms causing transitions between different states of marine ecosystems and to make significant scientific advances in their prediction.

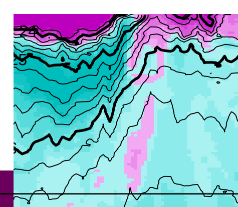
THE COMPLEX
COASTAL OCEAN

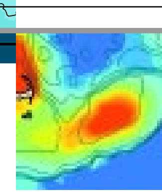
The ocean margin occupies only about 10% of the global ocean area and a much smaller fraction of its volume, but it dominates the economic importance of the sea, including activities such as fish harvest, sand and gravel mining, waste disposal, petroleum extraction and recreation. The land-ocean interface also represents the primary zone of human habitation in the US. Thus, the mutual influence of humans and ocean is strongly felt by each. Human impact on the coastal zone has been increasing. There is now an urgent need to gain a more complete understanding of the processes that influence and control this environment.

At the ocean margin, land, ocean, seafloor and atmosphere meet and interact to produce strong gradients in energy, material and biota. These strong gradients, and the proximal influence of a wide array of forcing functions (e.g., marine vs. terrestrial weather patterns), heighten environmental variance in this zone. Many marine processes, which affect mass and energy movement within the coastal ocean and across the different coastal boundaries, are also intensified. Understanding the workings of this complex region requires a more direct understanding of the different forcing functions that affect it and the *in situ* physical, chemical and biological processes controlling the ecosystem. Perturbations transferred from the terrestrial environment—for example, changing land use and hence river export—can lead to particularly complex responses in ocean margin environments.

The ocean margin traps biogenic materials and sediments, intensifying physical and chemical processes, and also dampening transfers of material between the land and open ocean. Estuaries and nearshore habitats are also sinks for many anthropogenic materials, especially nutrients, hydrocarbons and toxic contaminants that have increasingly serious ecological effects. This trapping depends heavily on the morphology of the ocean margin, for example, the shape of the estuary and adjacent shelf, which varies among regions and over geological time. Combinations of trapping, reflections and strong gradients allow the coastal ocean to act as







both a low-pass filter and an amplifier of terrestrial and oceanic processes. The filtering capacity of coastal ocean margins is influenced by its biological communities. The result is an environment that varies strongly in space and time, with especially important consequences for the human populations that reside near the coast, and for ecosystem processes that can propagate into the open ocean.

WHAT ARE THE BIG PROBLEMS?

This section focuses on three areas in which we see imminent rapid scientific progress. The first is fluxes of material from land to the sea, an area which has seen much progress but in which issues of variance, and basic science, sorely need advance. The second is the manner in which the physics of coastal environments drives other types of oceanic processes. The third focuses on the enormous potential influence of the open ocean on its thin edge and, conversely, the impact that this region of high fluxes and steep gradients can have on the open ocean.

Land-Ocean Fluxes

Material inputs to the coastal zone are largely unidirectional—from land to sea—and include organic and inorganic sediment, dissolved elements, airborne dust, and anthropogenic pollutants and nutrients. These inputs are influenced by the local watershed and meteorological characteristics and biogenic habitat quantity and quality. Human activities can also have a strong impact on the coastal ocean, both locally and remotely. Cumulatively, these material inputs have a major influence on the chemistry of the global ocean and need further study as fluxes of materials, especially nutrients and toxic contaminants, have greatly influenced ecosystem processes, including food web dynamics, biological production and community structure.

Inputs of biologically important materials. While we know patterns of water flow and major element composition of larger rivers reasonably well, there is less understanding of the chemical form of minor elements and organic matter that are transported from terrestrial watersheds into the coastal environment. Riverine organic matter is a vital term in the global carbon balance and minor elements are often critical to coastal and oceanic ecosystems. Lack of dissolved iron in some coastal upwelled waters can also be biolimiting unless iron inputs from land sources are available, and extensive blooms of large diatoms do not develop in these waters as they do in other upwelled waters containing sufficient iron. In some cases, estuaries act as important biogeochemical filters by removing excess nutrients and other minor elements during river/ocean mixing, but the relative roles of biological versus inorganic processes need better definition (e.g., for phosphate).

The total volume of groundwater discharge to the global ocean is relatively small, but locally groundwater can significantly influence the freshwater contributions. More importantly, however, groundwater often has far higher concentrations of dissolved species than do river water, affecting regional delivery of some dissolved ions (e.g., nitrate). Work on identifying important regions of groundwater influence, its role in material flux, and consequent ecosystem response is now accelerating. This area is ripe for significant advances, especially in composition and speciation of incoming groundwater, hydrological and geological controls on inflows, and patterns of dispersal in the oceans.

Sediment fluxes and episodic events. Globally, rivers deliver approximately 15 to 20 billion tons of suspended solids to the sea every year, often in short, episodic pulses. Once carried to the marine setting, sediments and associated materials can be trapped or dispersed along the coast, funneled into the deep-ocean basins , or where supply is high and the energy for dispersion is relatively low, left concentrated in large deltas. The processes by which sediments move from the riverine, through the estuarine, and out into the coastal ocean environments give rise to a wide variety of research opportunities. The high energies of tidal, wave and current movements at the ocean-land boundary tend to separate the sediment delivered by rivers by properties such as particle size. Understanding the processes by which these various components move across the coastal boundary region, or are trapped within it, is a great scientific challenge.

Sediments delivered by rivers are not chemically inert and may serve as source or sink for many materials (e.g., nutrients, pollutants) in the coastal ocean. This source or sink role may change as the particles change their depositional regime during subsequent resuspension or transport events. In short, many chemical elements, including pollutants such as heavy metals, share their immediate transport dynamics with the particles to which they are attached especially with fine-grained sediments.

An important area of research continues to focus on the time scales of sediment exchange between the water column and the bottom. While some aspects of sediment resuspension and transport are understood and supported by field measurements, the ability to predict and model sediment transport in many coastal settings is crude at best. This means that coastal sediment budgets cannot be constructed with any confidence, and the evolution of the shoreface and bottom topography cannot be predicted for different conditions, including highly episodic events such as storms and hurricanes. Some key questions include:

- *How are riverine sediments trapped in the coastal zone?* Terrestrial events that occur over a range of time and spatial scales can have a great impact on the margin ecosystem. The periodicity and impact of fluvial events depend on the hydrology and size of the watershed. Individual storm events tend to have a greater impact on arid watersheds and small rivers than on wet watersheds or large rivers. Small mountainous rivers discharge greater loads relative to the size of their drainage basins than do larger rivers. Most large rivers enter the ocean with very gentle gradients; thus, large reaches of the rivers (100s km) can be influenced by tides and/or estuarine processes. Even in these large systems, episodic events such as large coastal storms can cause large excursions from "average" riverine input values. In addition, episodic events can overwhelm the modulating influence of marsh, mangrove and estuarine processing of nutrients, with resulting large inputs of nutrients and pollutants to the outer margin. Currently, there is little quantitative knowledge available about the amount of sediment reaching the ocean, and little understanding of the processes related to sediment entrapment, in any of these fluvial regimes. For example, despite over 30 years of study, we still do not understand the role of the shoreface in barrier island evolution.
- *What is the impact of sediment fluxes on coastal ecosystems?* While sediment fluxes alter the quantity, quality and distribution of biogenic habitat and communities that have major influence on chemical and energy fluxes within coastal regions, the quantitative impact of episodic events on material fluxes is largely unknown. In estuaries, sea grass, salt marsh and once large populations of suspension-feeders (e.g., oysters) provide a biological filter that can offset loading of human-derived nutrients and other wastes. Influx of sediments

and associated changes in the geomorphology of estuaries can reduce, smother and degrade biogenic habitats, thereby reducing their ability to function as filters and provide essential nursery and foraging habitats for myriad economically and ecologically valuable species. In nearshore environments, sediment loading also has important negative effects on kelp forests and coral reefs that also function to provide habitat for highly diverse and productive biological communities. Episodic events need particular attention, as they can overwhelm the modulating influence of marsh, mangrove and estuarine processing, with resulting large inputs of nutrients and pollutants to the outer margin.

- *What are the important modes of fluid mud transport?* Until recently, fluid muds (suspended-sediment concentrations greater than 10 g/l) were considered to be restricted to estuarine settings and largely unimportant in the large-scale transport of fine-grained sediments. Hyperpycnal flows (underflows rich in sediment) have been observed to reach the ocean during large river floods, but density-driven gravity flows have not generally been considered to be important on continental shelves (see Sediment Transport box on opposite page). Such flows could move large masses of sediment, along with their adsorbed chemical species, across the gently sloping continental shelves, carrying pollutants to seafloor regions previously thought to be pristine. The non-Newtonian character of these fluid muds make them poorly understood agents for transport.

- *How are sedimentary terraces on continental margins constructed through time?* Over geologic time, the detailed structure of sedimentary terraces, which ring nearly all continental margins, records the interplay of the changes in accommodation space for sediment storage, in sediment supply, in sea level, and in sediment transport and deposition (Figure 12). It remains uncertain whether individual elements of this terrace are constructed by the integration of transport and deposition processes that take place over months and years or are dominated by the very large, episodic storm events that may occur only once in a century or

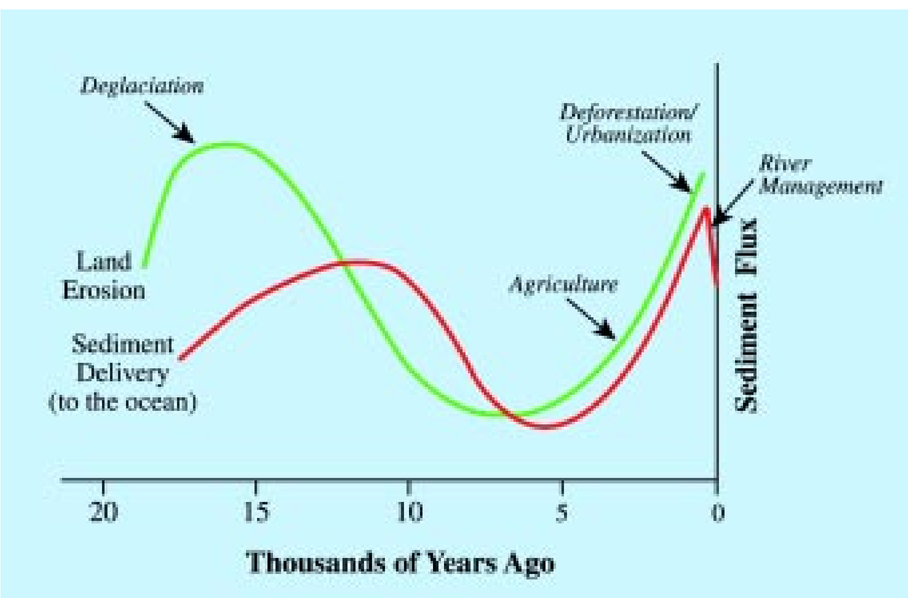
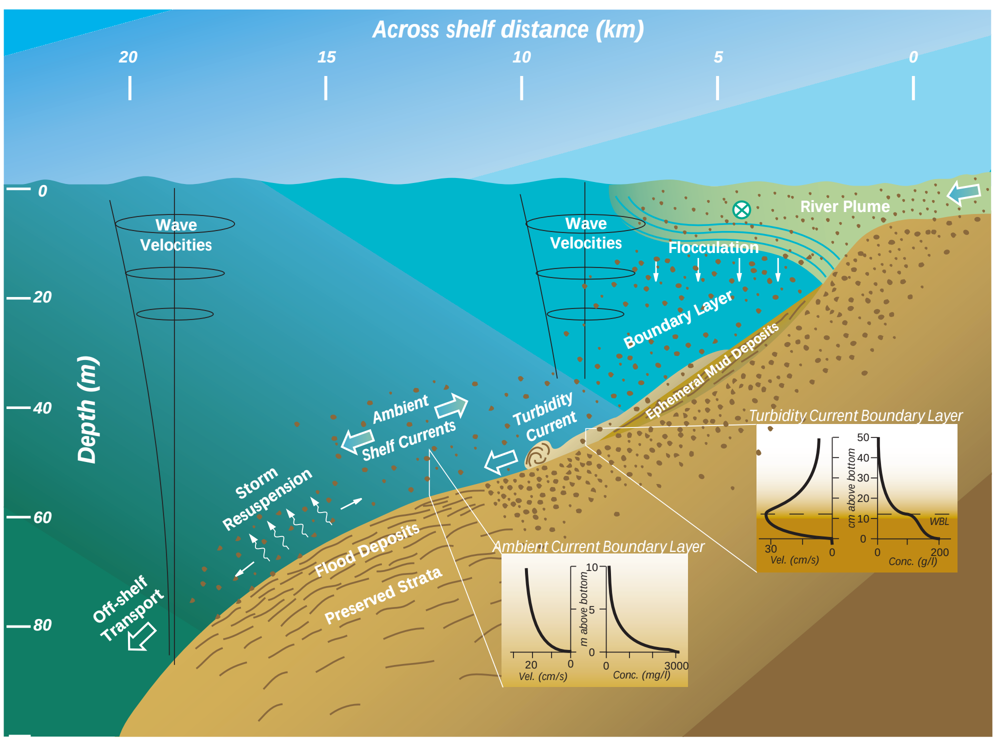


Figure 12. Over the past century, rivers have discharged annually about 35,000 km^3 of water and 20 x 10^9 tons of sediment to the ocean. Fluxes have changed over the past 20,000 years, and continue to do so. The abundant sediment eroded by glaciers during the last glacial maximum was transported fluvially as climate warmed, thus giving a time lag between erosion and sediment delivery to the ocean. Erosion, and thus ultimately sediment delivery, decreased throughout much of the Holocene, but increased (locally by an order of magnitude) with the advent of organized agriculture. Erosion has accelerated in the past century because of changing land-use, particularly in Africa and Asia. Global sediment delivery, however, is decreasing, the result of increased river management, particularly dam construction. Figure courtesy of J.D. Milliman, and is from J.D. Milliman and K.L. Farnsworth, River Discharge to the Ocean: A Global Analysis, Oxford University Press, in press.

Wave- and Density-Driven Sediment Transport

Contributed by Rocky Geyer and Peter Traykovski, Woods Hole Oceanographic Institution

Small rivers with mountainous catchment basins play a surprisingly significant role in the global supply of terrestrial sediment to the ocean (Milliman and Syvitski, 1992). The fast time response of theses systems makes their dynamics different from large rivers with a season response. The Eel River is one of several rivers in northern California that discharge freshwater at the coast. Because of the regional weather and the inland extent of the drainage basin, the discharge is highly event-driven, with a peak flux of 12,000 m^3/s measured during the extreme Jan. 1 1997 flood. *In situ* measurements made with helicopter- and ship-based profilers and moored sensors on the Eel River shelf during this event reveal a new physical mechanism for transporting sediment across the continental shelf. Observations of the sediment-laden plume by Geyer et al. (in press) indicate that the freshwater surface plume only delivers fine sediment as far as the inner shelf, but the sediment accumulates 5-10 km further offshore, in mid-shelf deposits (Wheatcroft et. al., 1997). Traykovski et al. (in press) have determined that gravitational flow of fluid mud within the surface gravity wave bottom boundary layer can provide the necessary cross-shelf sediment fluxes to explain this discrepancy. Although the wave boundary layer is only 10-15 cm thick, the suspended sediment concentration in the wave boundary layer was measured by an acoustic backscattering sensor at over 30g/l (in excess of the commonly accepted 10g/l fluid-mud concentration level). Velocities in this layer were estimated at 30 cm/s from extrapolating data from a vertical array of current meters immediately above the layer. Based on the concentration and velocity measurements the dynamics of this layer are consistent with a force balance between gravitational forcing of the downslope flow and frictional drag. The resulting cross-shelf flux can transport all of the plume-derived sediment from the inner shelf bottom boundary layer to the mid-shelf deposits in one to three days. These observations are particularly interesting because they document a gravity flow where the wave velocities provide the turbulence to keep the sediment in suspension as opposed to the turbulence generated by the downslope flow itself. In fact, as the wave energy at the seafloor decreases (either by the storm waning, or by the flow reaching deeper water) the fluid-mud flow becomes depositional. This can explain the observed mid-shelf location of mud deposits.



Schematic of the sediment-transport processes on the Eel River shelf. The sediment enters the shelf domain in the river plume, and it rains into the bottom boundary layer on the inner shelf at a rate determined by particle aggregation within the plume. Sediment accumulates within the boundary layer or deposits as ephemeral mud deposits on top of inner shelf sands, depending on the energy for wave resuspension. If the concentrations are high enough, then turbidity currents within the wave boundary layer transport the sediment to the mid-shelf deposits. Beyond mid-shelf depths the wave energy at the seafloor is insufficient to keep high enough concentrations in suspension to maintain the turbidity currents. Ambient currents in the bottom boundary layer also disperse the sediment, ultimately causing off-shelf transport due to preferential resuspension in the higher-energy inner-shelf region. Storm-resuspension remobilizes some of the sediment, and may result in sediment export off the shelf. Some fraction of the deposit is ultimately preserved as part of the geological record.

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millennium. We are only beginning to acquire a quantitative understanding of the processes that control the distribution of sediment accumulation among estuaries, shelves and slopes, especially as a function of varying sea level. Coastal processes and morphology during periods of low sea level are particularly unclear. We are only beginning to quantify the magnitude of sea-level change in the past (see Sea Level Rise box on opposite page), and we have serious doubts about the more simple models of tectonic subsidence along continental margins. Understanding the developmental history of Earth's primary depocenters is fundamental not only to the exploration for resources, but also to the understanding of Earth's tectonic pulses that build these thick sedimentary sections and then recycle them back into mountains ranges.

Carbon fluxes. Carbon fluxes in margin sediments are higher because of direct river input of terrigenous carbon, shallow depth that leads to efficient deposition, and higher overall ocean margin productivity especially in terms of new production. Despite sedimentary remineralization, these higher fluxes can result in relatively high efficiencies of organic carbon preservation in margin sediments (Figure 13). This preservation on geological time scales can influence the CO_2/O_2 balance of the atmosphere. The controls on this sequestration, at various time scales, are not well understood, but there should be a clear link to sediment dynamics.

Organic carbon buried in sediments may serve as a substrate for microbial activity within the sediments, and gives rise to gas hydrates in ocean margin settings. The reservoir size of this microbially produced gas is well over two orders of magnitude larger than that of proven global gas reserves. These hydrates may be significant in sediment movement as well as the carbon cycle and paleoclimate (see Global Warming box on page 28 and Gas Hydrates box on page 121). Their modern distribution is poorly known, as are their generation rate, migration pathways through the sediments, and rate of return to the ocean environment.

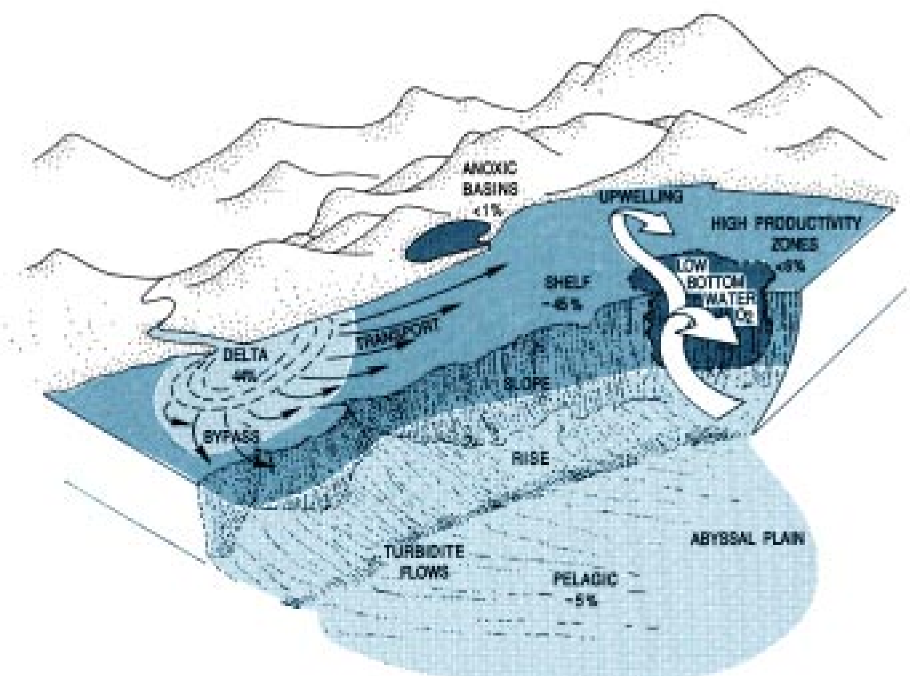

Figure 13. Carbon burial in oceanic sediments is dominantly on the ocean margins. Percentages of total burial on figure show that most occurs on shelves, divided between low-latitude deltaic depocenters and more normal shelf environments. Redrawn from J. Hedges, and R. Keil, Sedimentary organic matter preservation: An assessment and speculative synthesis, *Mar. Chem.* **49**, 81-115, 1995.

Sea Level Rise

Contributed by W. Sturges, Florida State University

There may be disputes about global warming, but people do not argue about sea level rise when beach-front buildings tumble into the ocean. Sea level is rising along all mid-latitude coasts; Charleston, South Carolina and Boston, Massachusetts are examples of the average trend (see figure). At high latitudes, however, the continents are still recovering from melting of glaciers. The land is emerging (so-called glacial rebound), and local sea level, in response, is going *down*, as shown along the Alaska coast. From the coasts of Alaska to Scandinavia, sea level is sinking at up to 6 mm/year. Although the continents can be either sinking or emerging depending on distance from the regions of ice loading, over most of the globe, sea level is unmistakably rising. Estimates of *global* sea level rise hover at just under 2 mm/year (Douglas, 2000). The best estimate of the present rate of rise is 2-3 mm/year on the East Coast of the US, and barely less than 2 mm/year on the West Coast. Where large reserves of natural gas or oil are being pumped out (or replaced), or where sediment loading is unusually great, the local rate of coastal sinking or rising can be affected more by human activity than by the large-scale effects of the ocean.

The largest single factor in sea-level change at most locations is the delayed response from glacial unloading, on time scales of thousands of years. Sea level was roughly 100 m lower during the last glacial maximum (ca. 20,000 years ago), and it has been rising at mid-latitudes ever since. On time scales of decades, forcing by winds over the open ocean causes variability of roughly ±10 cm. The melting of mid-latitude glaciers and the potential melting of high-latitude ice are obvious contributors to the mass of water in the oceans and are subjects of intense research. The expansion of sea water as it warms adds a small additional component to the rate of rise.

As the figure shows, sea level fluctuates chaotically over periods of a few years. Our inability to predict winds over the open ocean limits our ability to predict the variability of ocean forcing of sea level on decadal time scales. The effect of global warming on the addition of water from glacial melting is a topic of intense ongoing research. Melting of the Greenland and Antarctic ice cover would have enormous implications, and although the database is now developing, it is still new. Most geophysical quantities vary so much on decadal time scales that it can be highly misleading to draw conclusions based only on short records.

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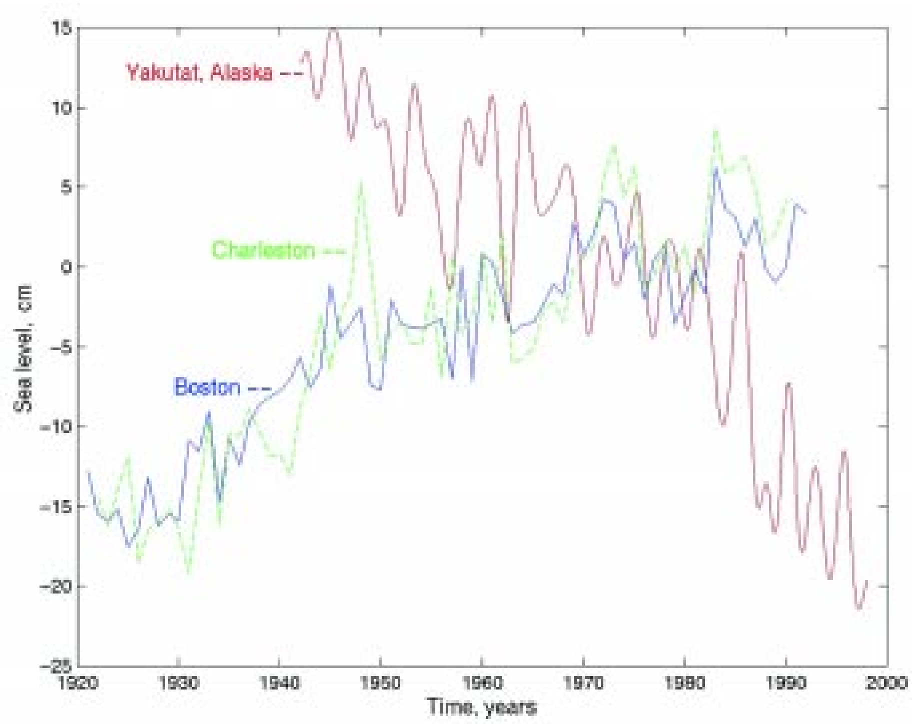


Sea level at Boston, Charleston, and Yakutat. Note both long-term trends and wind-driven interannual fluctuations (Sturges and Hong, 2000).

Anthropogenic influences. There is no question that human activities have affected and will continue to affect the coastal environment. Apart from some Arctic rivers and very large rivers (such as the Amazon, whose enormity has thus far defied human impact), human activity has had a moderate to very heavy impact on most rivers through deforestation, agriculture, flow modification and urbanization. Very few watersheds discharging into the ocean are in a natural state, and most are undergoing continual changes in land use. For example, farming activity is decreasing in some areas and is sometimes accompanied by reforestation, while in other areas, deforestation is increasing. Dams continue to be built in some areas, while in other areas dams may be removed. The coastal implications of dams are only now being documented, and predicting their consequences is almost impossible with our current understanding of coastal sedimentation, nutrient regimes and other issues. If we are to make rational and informed choices in meeting societal needs we must more fully understand the consequences of these activities.

Global river discharges of nitrogen and phosphorus, and total organic carbon may have doubled over the past two centuries, with much larger relative increases in some river and groundwater systems. Nitrogen to silica ratios in rivers have changed and probably caused shifts in coastal phytoplankton populations. Along with fishery exploitation, nutrient loading in estuaries and nearshore environments has had the largest impact on biological processes in coastal ecosystems. Nutrient loading through river discharge, ground water seepage and atmospheric deposition has been linked to major changes in the structure of biological communities in estuaries and coastal regions, as well as changes in the rates and processes that control community and population dynamics. Increasing eutrophication can further reduce water quality, increase the frequency and spatial extent of hypoxia/anoxia events, and generate harmful algal blooms (e.g., red tides, *Pfisteria*) that affect a spectrum of commercial industries and can harm human health. Though we have been able to monitor the consequences of irregular nutrient input, we have little knowledge of the complex chemical, biological and physical interactions that trigger harmful algal blooms so that we can ultimately predict, or take steps to avoid, their occurrence.

Human activity has not only affected rivers; it has also affected the atmosphere in terms of particulates, aerosols and chemicals. Although the general pattern of dust supply to the ocean is fairly well known, much less is known about the total flux and its variability, and how this flux affects biological systems through delivery of both contaminants and limiting micronutrients such as iron. Likewise, the potentially important role of wet deposition events in nutrient delivery to coastal waters is gaining appreciation. Eolian deposition of nutrients appears to be a major source of nutrient loading in coastal margins that may lead to eutrophication and associated ecological changes. Atmospheric inputs of particulates and nutrients can lead to both local and distant changes in the levels of primary and secondary production. Some of the atmospheric input of anthropogenic contaminants into the Northeast Pacific watersheds and coastal waters can now be traced back to massive dust storms in Asia. Whether this will become a significant contaminant source for the Northeast Pacific is unknown.

Trace element cycles may prove especially significant. Alterations of trace element concentrations in coastal environments can influence biological communities via both toxicity and biolimitation. Predictions from culture work indicate significant potential impacts on community structure at the base of marine food chains by the elevated levels of copper and zinc observed in some coastal areas. The balance between supply of macronutrients (e.g., N, P, Si) and trace nutrients (e.g., Fe) may regulate species composition and ecosystem structure. Such shifts in ecosystem structure can produce harmful algal blooms.

Land-derived inputs of toxic contaminants can influence biological processes from the cellular to ecosystem level. Changes associated with contaminant uptake in coastal fishes, invertebrates and mammals apparently reduce the reproduction, growth, condition and survival of individuals leading to changes in ecological interactions and subsequent ecosystem structure and function. The Exxon Valdez oil spill in Alaska and chronic PCB contamination in Puget Sound provide two clear examples of how land-derived contaminants released through human activities alter a wide spectrum of biological processes and ecological dynamics that impact inshore, offshore and terrestrial ecosystems. Defining the pathways of contaminants into the marine environment and their impact on the biota is critical to making informed decisions on control and remediation.

Greater research will be needed to determine the ecological effects of human and natural alterations in the quantity, quality and spatially explicit processes associated with coastal habitats. The distribution of coastal habitats (salt-marsh and oyster reefs, seagrass beds, kelp forests, coral reefs and mangroves) controls chemical and energy budgets and the production of economically valuable species. These habitats are being destroyed and degraded at an increasing rate as a result of human activity along the coast (see Coral Reef box on page 80). It is necessary to understand how coastal biogenic habitats function to provide essential resources to associated species, control rates of energy and material transfer and regulate geological processes. Efforts are also needed to identify and predict how global warming and sea level rise will affect the distribution, abundance and landscape connectivity of various habitat types and their influence on associated processes and species. Greater understanding of spatially explicit habitat processes is likely to improve our ability to manage and conserve exploited species. For example, fishery managers worldwide now recognize that effective management of declining coastal fisheries will be impossible without a better understanding of species-habitat associations, species interactions and the development of marine reserve systems. An integrated research program is required that involves multifaceted quantitative modeling, synthesis of existing biological and physical data from geographically diverse systems, and large-scale experiments to test spatially explicit interactions among energy and material transfers, species-species and species-habitat interactions. The development of marine reserve systems has increasingly been used as a management tool, but fundamental knowledge of the essential requirements of such systems is lacking.

Physically forced margin processes

A number of physical processes strongly influence the character of the coastal ocean environment. Episodic, large, wind-driven surface waves and storm surges can cause massive sediment movement, beach erosion and physical, chemical and biological modification to coastal estuaries, marshes and lagoons. In contrast, tides and tidal currents (including tidally generated internal wave currents) create a constant background of sediment movement, coastal water-level change and bottom-generated turbulent mixing. Freshwater flow from both point and distributed sources (including groundwater) into saline shelf water drives an estuarine circulation with a brackish transition zone where a number of key biochemical and sedimentary processes occur. Mid-latitude and tropical storms can create large wave- and wind-driven currents and surface mixing that can rework bedforms, reduce vertical stratification, restructure the coastline and significantly displace water, particles and biota. Continental climate regimes can accelerate surface cooling and heating of shelf waters. Deep-ocean features (e.g., boundary currents, eddies and rings) can also lap onto the shelf and directly affect coastal ocean environments. Factors such as surface buoyancy loss, increased turbidity and wave-induced re-suspension can cause rapid water mass sinking, transporting shelf material to slope depths on short time scales.

Understanding basic physical processes. Recent work gives a first-order understanding of many of the more basic physical processes at work in the coastal ocean. Some areas where important advances are being made and where we anticipate significant progress include:

- *Role of turbulent mixing in estuarine physics.* Vertical mixing has long been thought to control the "estuarine circulation" and salt budget in most estuaries, but only recently have *direct* turbulence measurements been made in a number of different estuaries (e.g., Hudson, San Francisco Bay, Columbia, Puget Sound). These measurements are providing a more comprehensive and quantitative understanding of vertical mixing processes, which play a fundamental role in most coastal physical and biological processes. For example, in the lower Hudson, the combination of the estuarine circulation and strong oscillatory tidal currents result in a distinct asymmetry in the vertical current and density structure over a tidal period, with the most intense Reynolds stresses occurring during flooding. Despite this variability over the tidal cycle, the mean along-estuary momentum remains a simple balance between bottom stress and the pressure gradient. The role of secondary circulation in horizontal mixing can now be investigated using new high-resolution hydrographic survey tools. These and similar advances presage a new era of quantitative estuarine research.

- *Behavior and dynamics of freshwater plumes.* The detailed behavior and dynamics of surface freshwater plumes flowing from coastal sources onto the shelf have been investigated both observationally and theoretically now for a number of large rivers (Amazon, Columbia), estuaries (Delaware, Chesapeake) and small rivers (Hudson, Connecticut, Eel). In all cases, the tendency for a buoyant plume to flow along the coast to the right of the source in the northern hemisphere can be augmented or countered by the direction and strength of the ambient along-shelf flow and direct wind forcing (i.e., up- or down-welling-favorable). Future research will evaluate the influence of a wide variety of other factors that all influence the plume's movement and evolution over space and time: the magnitude of the freshwater flux, its time dependence, the density contrast between plume and ambient water, the nature and strength of wind-driven vertical mixing near the surface and bottom interfaces of the plume, the ambient shelf circulation, and bottom topography. These studies will have wide interdisciplinary application, because river plumes are one of the primary sources of freshwater, nutrients, pollutants and sediment to the coastal ocean. River plumes can also spread harmful algal blooms along the coast, so predicting the behavior of plumes has direct societal benefits.

- *Dynamics of the surf zone and inner shelf.* Interest in the complex wave-driven currents and sediment movement in the surf-zone has been reinvigorated by new methods to deploy high-frequency, three-dimensional current sensors and other instrumentation in this highly turbulent area. For example, measurements off Duck, NC show how storm-driven waves shoaling over a bumpy sloping bottom generate a bottom stress pattern that reshapes the beach morphology with dynamic feedback to the waves and bottom stress field (see Turbulence Dynamics box on page 68). The inner shelf—where surface and bottom boundary layers merge—is also a dynamic feature. It is in this zone where the onshore (offshore) transport in the upper layer decreases from the mid-shelf Ekman flux to zero at the coast during wind-driven downwelling (upwelling), thus forming the "coastal wall" traditionally used as the shallow boundary condition in analytic and numerical shelf circulation models. Recent theory suggests that the inner shelf responds quite differently to upwelling versus downwelling winds, due to the interplay of cross-shelf density advection and vertical turbulent mixing. Field studies of the inner shelf are just beginning to examine this prediction, which has important implications for along- and cross-shelf transport of water and material during wind events.
- *Dynamics of wind-driven currents.* A major accomplishment of the last two decades has been the development of coastal-trapped wave (CTW) theory and its verification through field studies around the world. In particular, the ability of continental margins to act as one-way waveguides for low-frequency waves (with time scales of 1 to 20 days typically) energetic over the shelf and upper slope is now well understood, and the application of this theory to the generation of along-shelf currents by local and remote wind forcing has been demonstrated in a number of regions with relatively simple topography. A prime example is the southward along-shelf currents driven along the US West Coast by large-scale upwelling-favorable winds during summer (as evidenced by the cold upwelled water seen in Figure 14). Along-shelf differences in topography and wind forcing contribute predictably to variations in along-shelf flow.

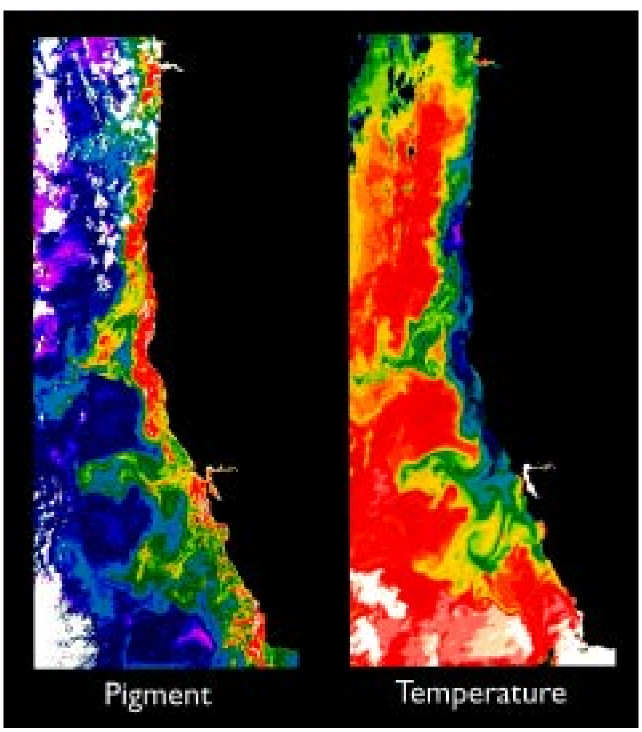


Figure 14. Satellite-derived images of sea surface temperature (right) and pigment (left) obtained during a summer period of active wind-driven upwelling. The coldest waters (dark blue) along the coast show regions of enhanced upwelling. Note the high pigment concentrations in the upwelled water found far from the coast, as well as the greater spatial complexity close to shore. Figure courtesy of Mark Abbott, Oregon State University.

Attempts to use CTW theory to predict the cross-shelf flow have proved illusive because this flow appears much more sensitive to small-scale variations in topography and possibly wind forcing. One striking aspect of Figure 14 is the tendency for upwelled water and biota to leave the shelf near capes. Recent drifter and high-resolution SeaSoar/ADCP studies show that an upwelling jet forms over the shelf off central Oregon and appears to be deflected into deep water by a submarine bank far from the start of the California Current (Figure 15). While there is much more to learn, it is clear that the detailed nature of regional topography and wind forcing on scales as small as a few kilometers can strongly influence the shelf flow regime and the off-shelf transport of shelf water and biota (Figure 14).

- *The bottom boundary layer.* As a result of the shallowness of the estuary and shelf, turbulent drag and mixing generated by near-bottom flow can play a central controlling role in many coastal processes. The combination of nearly oscillatory gravity wave currents with tidal and lower-frequency flows over complex and moveable

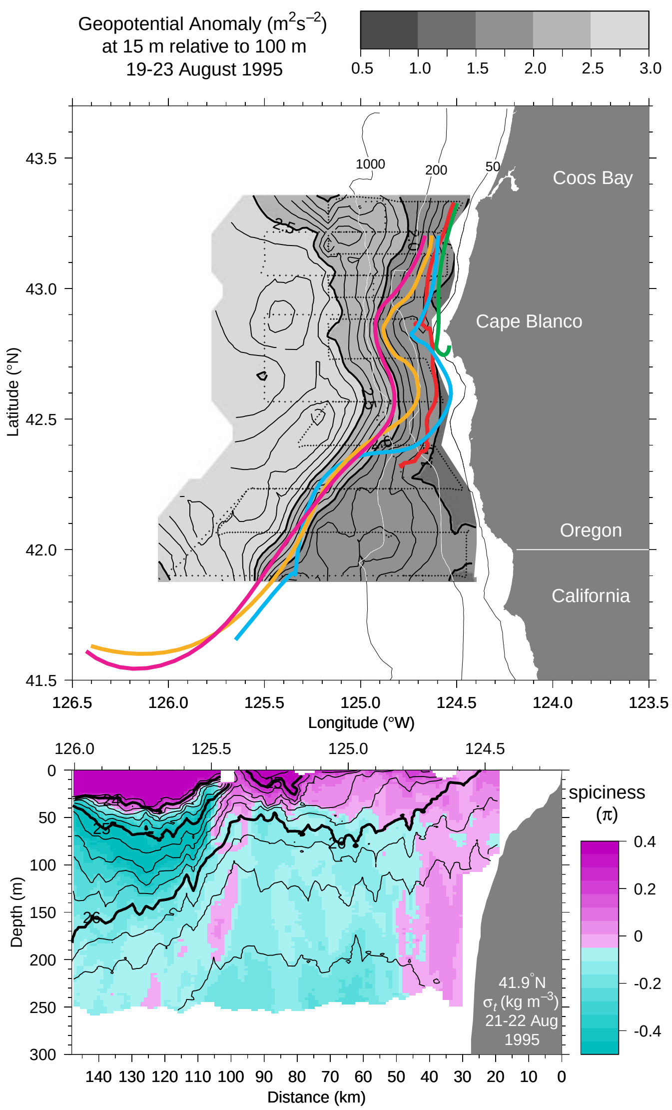


Figure 15. The trajectories of satellite-tracked surface drifters for 19-30 August 1995 and contours of dynamic height derived from SeaSoar density measurements show the separation of a coastal upwelling jet near Cape Blanco, Oregon (top). A vertical section downstream of the Cape reveals strongly upwelled isopycnals associated with the separated jet located around 100 km offshore (bottom). At depth, the separated, equatorward jet interacts with a poleward undercurrent such that water from the undercurrent is pulled offshore and joins the equatorward flow to augment its total transport. The undercurrent water is relatively warm and salty, hence "spicy," a property combining temperature and salinity and orthogonal to density in a T-S diagram. A vertical section of spiciness derived from SeaSoar measurements provides evidence that a portion of the undercurrent (near 150 m, 100 km offshore) has turned offshore and equatorward to join the separated jet. Figure adapted from Barth, J.A., S.D. Pierce and R.L. Smith, A separating coastal upwelling jet at Cape Blanco, Oregon and its connection to the California Current System, *Deep-Sea Res. II*, **47**, 783-810, 2000.

bed-forms greatly hinder detailed flow measurements within a few centimeters of the bottom. However, above a few centimeters, new acoustic current sensing approaches allow accurate measurement of the three-dimensional turbulent flow near the bottom, and recent studies are starting to provide direct tests of some of our basic ideas about bottom boundary layers. For example, on the relatively smooth flat New England shelf, the shear production and dissipation terms in the turbulent kinetic energy equation were determined independently. Within a few meters above bottom, these terms balance within experimental error, providing the first *in situ* confirmation of the production-dissipation energy balance that is commonly assumed to hold in boundary layer studies (see Turbulence Dynamics box on page 68). In contrast, the Prandtl-Karman "law of the wall," a semi-empirical relationship between turbulent shear stress and vertical derivative of horizontal velocity, has proven to be quantitatively inaccurate in some shelf, estuarine and surfzone bottom boundary layers. Presumably, observed departures from the law of the wall are due to stable stratification, but they are too large to be explained by local application of the atmospheric Monin-Obukhov similarity theory, and their proper interpretation is a subject of current research.

Recent theory and limited observation show a pronounced asymmetry in bottom layer structure depending on the direction of the overlying flow. When deeper (denser) water is carried up the shelf in the bottom layer, the density difference at the top of the layer increases, reducing vertical mixing and resulting in a thinner bottom layer. When shallow (lighter) water is carried down the shelf, the vertical density difference decreases, increasing vertical mixing and resulting in a thicker layer. In this region further above the bottom, the dynamics become more complex, as stratification (due to temperature, salinity or suspended sediment), bottom slope, and the direction and strength of the overlying flow all influence the character and height of the boundary layer. Future field studies designed to investigate this predicted asymmetry will describe this basic phenomenon as it occurs in the coastal ocean and provide a critical test of new models of vertical turbulent mixing. It is essential to note that vertical mixing plays such a fundamental role of coastal dynamics that it needs to be better understood and parameterized in order for numerical physical and coupled physical/biological models to provide realistic simulations.

- *Shelf-break Fronts.* The combination of rapid survey tools (such as SeaSoar and the shipboard ADCP) with precision navigation is providing new high-resolution descriptions of the fronts between shelf and ocean waters found near the shelf break along many continental margins. The shelf-break front along the Northeast US provides a clear example of this emerging picture. The cross-front scale is only 10 to 20 km, resulting in strong horizontal density gradients and large vertical and horizontal current shears, with peak currents in the near-surface core of the jet of up to 40 to 80 cm/s (Figure 16). In addition, a vigorous secondary circulation has been observed using dye releases. The shelf-break jet transports a significant fraction of the along-shelf flux of shelf water, and supplies the shelf water carried off shelf as streamers around warm-core rings. Strong shelf-break jets have now been found in the Labrador Sea, Black Sea, West Florida Shelf and South China Sea. The existence of these fronts may have been identified in historical hydrographic data, but their detailed thermohaline and velocity structure can now be quantified. While the importance of shelf break jets is only starting to emerge, it is clear that they can maintain their identity over long distances and thus transport shelf water far along the continental margin. The impact of this process on material transport, the spread of marine organisms and formation of geobiological domains, is not currently understood.

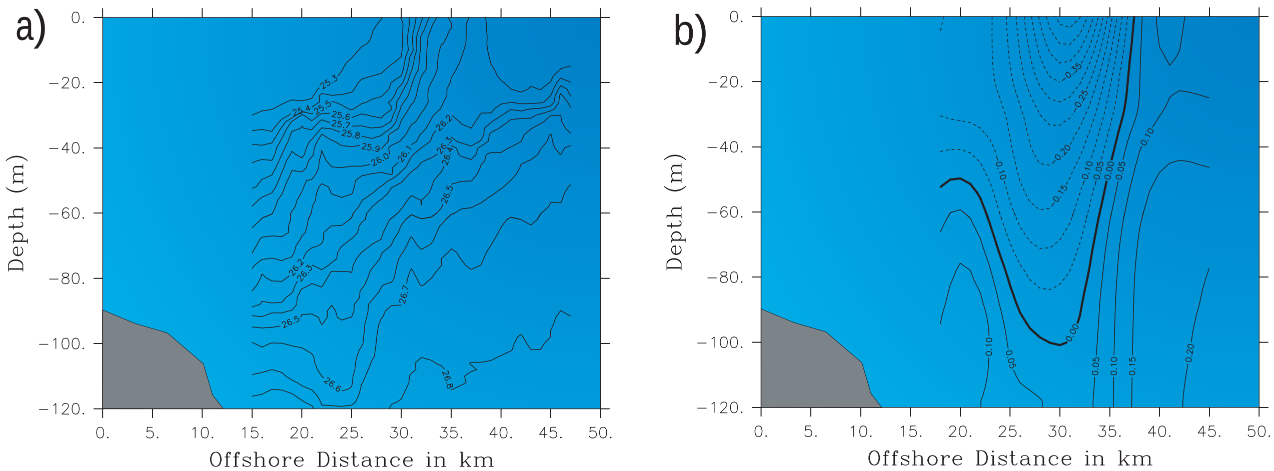


Figure 16. A high resolution density and velocity section across the shelfbreak south of New England in the Middle Atlantic Bight. The density section (panel a) shows strong cross-shelf density gradients which stretch from the bottom to the surface, with particularly strong gradients in the upper 20 m of the water column. The contour interval is 0.1 kg/m^3. The alongshelf velocity (panel b) shows a strong jet with a maximum velocity of 0.5 m/s which is relatively narrow (10 km). The contour interval is 0.05 m/s, with dashed contours representing westward flow and solid contours eastward flow. Figure courtesy of Glen Gawarkiewicz, Woods Hole Oceanographic Institution, modified from G. Gawarkiewicz, F. Bahr, R. Beardsley, K Brink, Interaction of a slope eddy with the shelfbreak front in the Middle Atlantic Bight, *J. Phys. Oceanogr.*, accepted, 2000.

Important advances are being made in other areas of the physics of the coastal zone. These include coastal meteorology, the effects of surface wave breaking in air-sea interaction (see Effects of Surface Waves box on page 66), the use of high-resolution numerical weather prediction models to describe the surface forcing on the coastal oceans, and the development and increased use of numerical circulation models for estuarine and shelf studies.

Physical Forcing and Variability of Biological Processes in the Coastal Zone. While some effects of physical forcing have been established, there is great uncertainty in the mechanisms by which they influence variability in biological phenomena. Some pelagic ecosystems are strongly dependent on large scale and mesoscale physical forcing. A prime example is the Northeast Pacific coastal upwelling zone stretching from California to Alaska. The water properties and currents in this zone are strongly influenced by large-scale, coupled ocean-atmospheric processes (e.g., El Niño, the North Pacific Decadal Oscillation), coastal runoff and mesoscale processes (e.g., supercritical surface winds near points, upwelling jets and eddies generated both on and off the shelf). Recent work on salmon, an important regional fishery, suggests that large fluctuations in stock occurred before intensive fishing, indicating that trying to sort out the ecological influences of the different physical processes in this region will be very difficult. Such sorting out will need to be done if we want to predict the impact of climate change on this fishery.

The effects of physical processes on coastal biological communities can be quite dramatic (see Larval Transport box on the opposite page) and can help explain the tremendous variance in coastal biological data sets. On the West Coast, dramatic fluctuations of crab, salmon and other fish populations occur on five to seven year (ENSO) cycles, as well as decadal cycles and longer (30-year time scales are known, but the relative roles

Wind-Driven Larval Transport

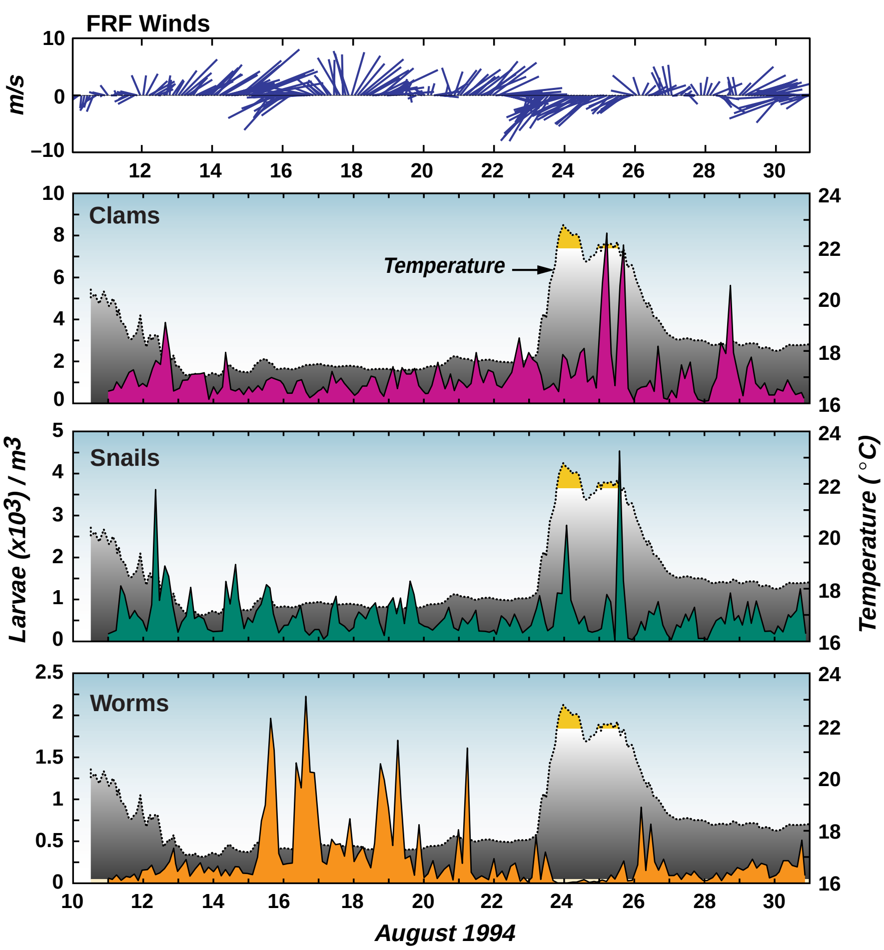
Contributed by Cheryl Ann Butman, University of California, Los Angeles and Steven J. Lentz, Woods Hole Oceanographic Institution

Most invertebrates – clams, snails, and worms – associated with sediments as adults have a planktonic larval stage. Dispersing in the water column for hours to months, the larvae eventually settle onto the seabed and metamorphose into benthic juveniles. The objective of NSF's Coastal Ocean Processes (CoOP) study on larval transport across the inner shelf was to identify the physical or biological processes most likely responsible for observed temporal and spatial variations in larval concentration.

The study took place during August-October, 1994 on the Outer Banks at Duck, North Carolina. A moored cross-shelf instrument array spanned water depths of 8 to 26 m and distances of 1 to 17 km from shore. During August, the inshore water column alternated between stratified and unstratified conditions. The 21-m mooring site, for example, was stratified most of the time, but intense or sustained upwelling conditions (northwestward winds) resulted in brief periods of a homogeneously cold water column, and one strong downwelling period (southwestward winds, Aug. 23-25) resulted in a uniformly warm water column for several days (Figure). Time series of larval concentration, at all depths and cross-shelf locations, showed striking variability on time scales of hours to weeks. Worm larval concentrations, for example, varied by three orders of magnitude over a day or less. Moreover, significant diurnal variations were detected in clam, snail and worm time-series, patterns that may result from active vertical migrations of the larvae.

Temporal variability in biological and physical variables on scales of days to weeks reflects processes that may transport larvae long distances. A plausible cross-shelf transport mechanism was revealed from patterns of low-frequency variability in larval concentration relative to subtidal variation in water temperature. Near the bottom at the 21 m site, clam and snail larval concentrations were low when the water was cold (upwelling conditions), and maximal peaks occurred when the water was warm (downwelling conditions). Worm larvae showed the opposite trend – maximal abundances in cold water and lower abundances in warm water.

These patterns may be due to the habitat affinities of the different taxa relative to the direction of cross-shelf transport over their habitats. Soft-bodied worms tend to live in muddy sediments offshore, whereas shelled clams and snails can withstand rougher conditions characteristic of sandy areas inshore. Thus, during upwelling, the cold, near-bottom water overlying offshore muds may transport worm larvae as it moves onshore, and across the 21-m near-bottom pump. In contrast, during downwelling, warm, shallow water over nearshore sands may transport clam and snail larvae as it moves offshore, and past the near-bed pump at the 21 m site. In this way, larvae originating from adults living on the seafloor can be carried shoreward and upward, or downward and seaward, depending on the direction of the wind-driven cross-shelf currents. Riding the coattails of such flows, larvae move much larger distances than they can swim. Whether the animals exploit these flow patterns or are simply at their mercy is a vital question for future study.



Top: Wind velocity vectors from measurements taken at the Army Corps of Engineers Field Research Facility (FRF) pier (Duck, NC). Bottom three graphs: Time series of larval concentration from the bottom-most pump (18.8 m depth), and water temperature at the bottom-most thermistor (19.0 m depth) at the 21-m mooring site. Larval samples (250 liters) were collected every three hours.

of changes in wind-driven primary productivity, larval transport and range shifts of predators are not understood). While at various locations these coastal communities have much in common, there are frequently major differences in both species composition and abundance over short distances. These differences partly result from differences in physical habitat (e.g., rocky vs. mud bottom, temperature gradients, intensity of bottom turbulence), but partly result from physical barriers and preferential pathways in alongshore transport. Much still needs to be learned about what physical and biological processes control the distribution of coastal benthic animals. This information is critical to any attempt to make marine reserves successful, especially since each species may have quite different environmental conditions for successful reproduction and recruitment.

Relatively little is known about how subtidal flows affect transport and dispersal of organisms, particularly larvae, throughout potential coastal habitats. Most marine species have a dispersing larval stage, which is a critical component of recruitment, yet the transport paths of these larvae are largely unknown. The effects of buoyancy- and wind-forced circulation, nonlinear tidal flow and topographic features on retention and redistribution of larvae have been observed, but our increasing understanding of coastal circulation has not been extended to this critical biological effect. Recent developments in elemental fingerprinting and population genetics are promising tools, but the eventual resolution of this issue will depend on well-focused interdisciplinary field studies coupled with improved biological/physical models. Physical models representing features on horizontal scales of one kilometer (or less) over dispersal distances of hundreds of kilometers are needed in many cases. Further study of vertical migratory behavior of larvae and secondary settlement, i.e., active or passive behavior that results in redistribution of settled juveniles by subsequent flow and sediment-transport events, is needed. Smaller-scale physical mixing also affects biological processes such as chemosensing, gamete dispersal, fertilization success and settling, which play critical roles in reproduction, prey avoidance, and food location and identification. Physical barriers are often broken down by anthropogenic means (e.g., transfer of alien species from foreign ports) with largely unpredictable, but often negative, effects on coastal ecosystems. Empirical rates of spread of these invading organisms have been determined, but the understanding of underlying biological/physical control mechanisms is needed to make vital predictions of these rates are lacking.

Turbulent processes influence many features in the coastal ocean (e.g., boundary layers, water mass formation, animal behavior, sediment movement). Recent field studies using high-frequency ADCP, microstructure sensors and purposeful tracer releases to investigate physical advection and turbulent mixing in the coastal ocean have revealed the complexity of the interactions that occur (see Tracer Release and Coastal Mixing boxes on pages 57 and 60). As noted in the Ocean Turbulence chapter, a window of opportunity is now open to examine biological responses to these interactions. One zone in which progress in our quantitative understanding of turbulence will yield much fruit is the benthic boundary layer. This zone has received attention as the site where sediment exchanges with the water column in the vertical, but it is also emerging as an important zone for horizontal movement (e.g., for off-shelf transport). Resuspension of sediments introduce particles, biota and chemicals to the water column; however, these fluxes have been studied mostly in lower energy situations. "Storm-chasing" has proven difficult from ship platforms, but new *in situ* sampling technologies will elucidate the importance of resuspension in higher energy events.

Exchange with the Open Ocean

Morphology strongly affects how ocean margins exchange with the open ocean. Coastal regimes may or may not include extensive estuarine regimes, and have shelves that vary in width, relief and depth. The degree to which these coastal systems trap material exiting the continents or import materials from the open ocean varies dramatically. Thus, processes controlling margins' ability to export to the open ocean and import and process material originating from the open ocean, become two areas of great significance for further study.

Materials export to the open ocean. Localized export of material to the open ocean can have global importance. As an example, mountainous New Guinea, with its tectonically young and easily weatherable rocks, hot weather and high rainfall, exports as much sediment as that discharged by all North American rivers. Sediment discharged from the north side of New Guinea area largely bypasses a very narrow shelf and escapes seaward, injecting dissolved and particulate matter into an undercurrent that contributes to the Pacific Equatorial Undercurrent. This process may be the major source of Fe to the equatorial Pacific, and cycles of productivity observed ten thousand kilometers away, in the eastern equatorial Pacific, may reflect these localized tectonic and weathering processes in New Guinea. In contrast, most Fe in the organic-rich rivers of the southeast US is flocculated in estuaries, inhibiting its flux to the open ocean.

Classic thought has been that during high stands of sea level, similar to present-day conditions, sediment was trapped in estuaries or on continental shelves. Very little sediment was thought to be lost to the deep sea (i.e., beyond the shelf break). However, several recent studies suggest that a large portion of fluvial sediment (>80%) is lost seaward from at least some estuaries, and that much is deposited as turbidite-like layers >5 cm thick. This is especially true for rivers emptying onto narrow, steep shelves. And these are the same systems that receive the dominant (>50) amount of global sediment flux from land. This has a significant impact on thought about mass transfer and evolution of continental-margin architecture, and also impacts the fate of components that are carried by the particles (e.g., carbon). The export and deep burial of carbon would greatly influence its fate (e.g., remineralization) and its role in greenhouse gases.

Coastal regimes have high primary production, much of it available for export. A large portion of the particle flux from the ocean margin to the open ocean may occur as density-driven, particle-rich fluids—denser ones along the bottom, more dilute fine-grained suspensions that flow along isopycnal surfaces, and surface flows of upwelled water with high concentrations of phytoplankton (Figure 14). Particles in these flows carry a variety of associated chemicals into the open marine environment. Because sedimentary organic matter and its affiliated elements are more efficiently remineralized in deep-ocean sediments, materials otherwise headed for burial will be returned to the water column. The magnitude of this transport and the extent to which the transfer of materials and chemical species is dominated by event-driven episodes are not well known.

Along much of the modern continental margins, fine-grained sediments and associated organics from the shelves are trapped in slope regions where they strongly influence the benthic community. In other regions, isopycnal flows of suspended solids and adsorbed chemicals extend hundreds of kilometers offshore and only gradually settle out as a hemipelagic drape of land-derived clays. The controls on the effectiveness of trapping on the slope are unclear. However, there are numerous opportunities for sedimentary particles to be temporarily stored between estuaries and the deep ocean, and particle exchange with the open ocean draws heavily on the two previously identified "problem" areas, namely, physically forced margin processes and land-ocean fluxes.

Trace and minor element concentrations in coastal water columns are often much different from those of the open ocean. Water movement offshore can result in significant perturbation in their concentrations in the open ocean environment. As coastal water with high oxygen demand is advected offshore and remineralization proceeds, large-scale oxygen minima appear. Biogeochemically active elements such as Fe, Mn and C all exhibit deep-water maxima due to offshore transport. The impact of these exports on global budgets needs a better quantitative definition.

Processing of imported material. The intensity of processes on the margins makes them potent modifiers of ocean water that is forced to flow up onto the slope and shelf. As an example, the global nitrogen cycle is strongly dependent on denitrification that occurs on the ocean margins. Denitrification is enhanced primarily as a result of a combination of shallow depth and lower oxygen concentrations at the sediment-water interface, causing nitrate derived from the open ocean to be converted to nitrogen gas and eventually returned to the atmosphere. Water residence time is a critical parameter in this loss term. Habitat alteration from processes such as altered sediment delivery may influence this denitrification process. These processes are clearly significant at the global level. Quantifying these exchanges will require physical oceanographers to determine the magnitude and time-dependent nature of shelf-open ocean or sediment-water fluxes in interdisciplinary efforts with marine geologists, biologists and biogeochemists.

WHAT MAKES PROGRESS POSSIBLE NOW?

While many factors will play a role in advancing the oceanography of ocean margins, two are particularly noteworthy. First, the problems on the margins are made especially difficult by the complexity of these areas, and second, many problems have lacked the appropriate sensing capability.

- **Conquering complexity.** The complexity and variability, both spatial and temporal, of the coastal oceans have always presented daunting challenges to marine scientists trying to develop a broader understanding of the processes that influence and control this dynamic environment. The devil has been often in the details, with the details often intractable in spite of satisfactory understanding of the relevant principles. For example, topography is critically important to many coastal processes, but varies considerably among coastal regions; this combination has inhibited generic coastal research by tending to restrict research conclusions to the sites in which they were investigated. The role of high variance has been difficult to assess in the past because of meager data-gathering capabilities for many important variables. The high temporal variability and great heterogeneity of water and material transport within and along the continental margins have made any study of material reactivity a difficult task. Assessing the role of the coastal ocean in the carbon cycle faces difficulties similar to its assessment in the equally variable terrestrial ecosystem.

  Fortunately, the advent of new sampling and monitoring technologies promises tremendous advance in the near future, especially in elucidating the very important role of episodic, high-energy events that may play a major role in some aspects of the coastal environment. Recent advances in remote sensing, continuous chemical sensing, and the application of tracers presage significant progress in understanding coastal processes occurring on short and long time scales. New tools include HF radar, acoustic and optical imaging systems deployed on towed bodies, Remotely operated vehicles, and moorings, towed microstructure, bio-optical and chemical sensors, isopycnal floats and GPS drifters, and better moored instruments, samplers and mooring technology.

- **New eyes.** As in any science, the advent of new sensing capabilities often leads to breakthroughs and the science of ocean margins is no exception. As an example, recent advances in several areas have set the stage for rapid progress in understanding micronutrient-biota interactions, including: (1) methods to determine speciation of bioactive trace metals, (2) understanding the biochemical role these metals play and their uptake mechanisms at the molecular level, (3) molecular tools to study these processes in the field with great sensitivity and selectivity, and (4) protocols to trace small water "patches" in the upper ocean, enabling manipulative experiments. Another example is the ability to see for the first time km scale circulation features in surface currents using HF radar. These circulation features affect transport of larvae and other biologically important material, over areas of thousands of square kilometers. Developing methods for assimilation of these and other subsurface data into physical models will not only allow a better tracking of the transport of anthropogenic materials and larval stages of marine organisms, it will aid in a better understanding of primary and secondary biological productivity and subsequent transport of this production.

Biological Data Assimilation

Contributed by Dennis McGillicuddy, Woods Hole Oceanographic Institution

Coupled physical-biological models offer a framework for dissection of the diverse assemblage of processes which influence the structure of planktonic populations. However, their utility is predicated on an ability to construct a simulation which is representative of the natural system. One technique for doing so (the "forward" problem) is to initialize a coupled model with a set of observations, integrate forward in time and then compare with the next set of observations. A successful outcome results in minor discrepancies between observations and predictions, and the model solutions thus can be used as a basis for diagnosis of the processes controlling the observed behavior. Unfortunately, satisfactory completion of the forward problem is not always achievable due to limitations in the models, the observations, or both. Adjoint data assimilation methods provide an alternative approach which is particularly useful in such cases. These techniques can be used to determine the model inputs (e.g., parameters, forcing functions) that minimize the misfit between observations and predictions, thereby producing an optimal solution from which the underlying dynamics can be gleaned.

An example of this approach is shown below, in which the adjoint method was used to diagnose physical and biological controls on *Pseudocalanus* spp. in the Gulf of Maine-Georges Bank region. The forward model is posed as an advection-diffusion-reaction equation for the concentration of this copepod. The inversion procedure is used to determine the biological sources and sinks (i.e., the "reaction" term) implied by the changes in abundance over time and the circulation during the intervening period. This analysis reveals geographically specific patterns in sources (red shading) and sinks (blue shading). These spatial patterns vary seasonally according to the animal distributions, the circulation, and their orientation with respect to each other. In cases when the flow is either weak or aligned with gradients in organism abundance, changes in concentration over time are dominated local population dynamics. Such is the case during this time period in the western Gulf of Maine, where the moderate increase in *Pseudocalanus* abundance is largely a result of the localized area of growth extending from just north of Cape Ann down into Cape Cod Bay. In contrast, where strong currents cut cross the gradients of abundance, a complex three-way balance arises between the local tendency, advective transport, and the population dynamics. Note that the area of net growth is centered slightly upstream of where the highest concentration of *Pseudocalanus* occurs.

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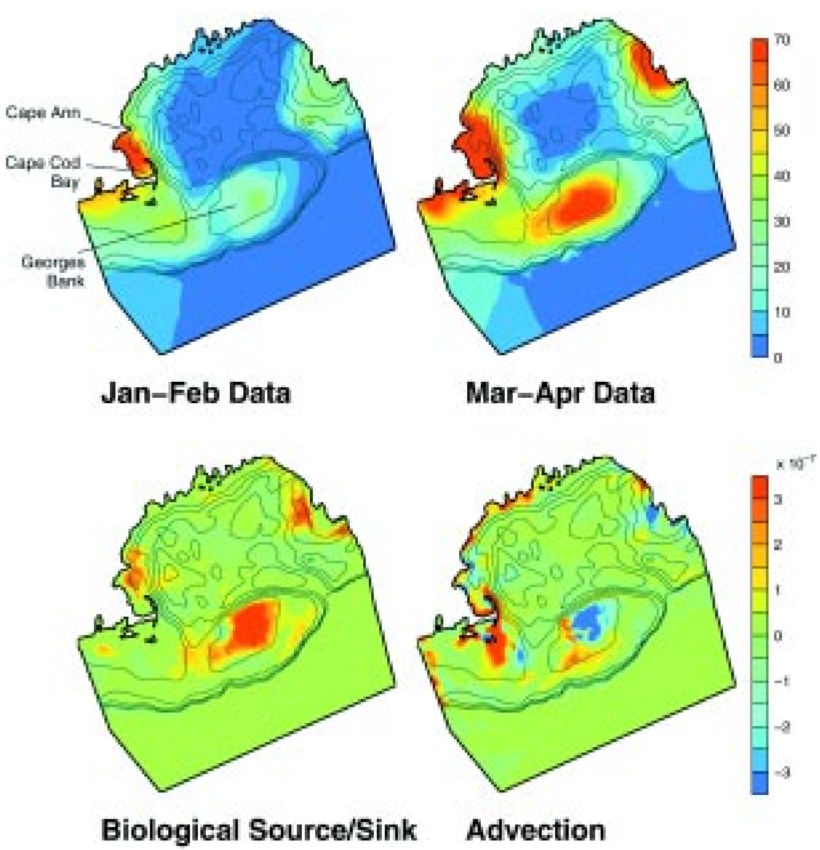


Climatological distributions of Pseudocalanus spp. for (a) January-February and (b) March-April derived from ten years of MARMAP observations (number of animals per m^3). Panel (c) shows the spatial distribution of the biological sources and sinks required to match these observations given the climatological circulation (not shown) during this period; panel (d) shows the net advective fluxes, averaged over the sixty days of integration. Units in (c) and (d) are number of animals per m^4 per second; the sign convention is such that the change over time is the sum of these two terms.

WHAT IS REQUIRED FOR PROGRESS?

Progress toward a better understanding of the coastal environment and the processes that control it involve two different aspects of our science. First is the development and use of appropriate technology, and the second is a research emphasis on critical physical, biological, chemical and geologic processes and the key regions in which they take place.

- **Long-term time-series.** We cannot expect to fully understand dynamic coastal ocean systems that can exhibit large interannual changes without a greater emphasis on monitoring these systems. Observing a system over an extended period time allows us to determine how the system responds to major natural changes. For example, in the coastal benthic communities, organisms will shift in response to changed substrate conditions, but we have little sense for how colonization rates respond to new substrate or various components of the community shift again with evolution back to "normal" sediment substrate. Chemical properties and fluxes, for example, contaminant return to the water column or carbon burial mechanisms, will present similar problems. Our ability to predict these changes depends on having understood each process at all of the relevant time scales. Our current inventory of studies is biased, as a result of the access allowed by previous technologies, toward snapshots and short-term process studies—the latter with time scales bounded in both the short- and long-term. New technologies and new funding models will enable extension of our snapshot and movie collections to greater ranges of time scales, and are clearly necessary to answer important coastal problems. Also needed is an increased multi-disciplinary and multi-agency effort in coastal environmental monitoring and, perhaps, enhancement of the role of existing marine laboratories in monitoring to the level of a nationally (or at least coastally) coordinated mission. Because the spatial and temporal complexity of the coastal ocean results in so many perturbations, greater understanding of its "natural" dynamics will provide the basis for prediction of anthropogenic perturbations of various types.

- **Interdisciplinary model systems.** Because biological and chemical measurements are often difficult and time consuming, it is rarely possible to observe these variables at the same space and time scales that physical properties can be sampled. In spite of some outstanding examples of novel instrument development allowing simultaneous synoptic physical and biological data sets (e.g., remote sensing, the Video Plankton Recorder, and new multifrequency acoustic methods), point measurements taken from discrete water samples and net tows will likely continue to dominate biological and chemical data sets. Analysis of such necessarily sparse observations in the context of a high physical variability calls for the use of realistic interdisciplinary model systems. In concert with data assimilation methods (see Data Assimilation box on opposite page), such systems can be used to construct optimal estimates of oceanic fields that agree with observations where they are available and are dynamically interpolated across data-sparse regions. These continuous space-time representations of the ocean provide a framework for detailed diagnosis of complexly coupled processes.

- **Field studies of ocean turbulence.** Because turbulent mixing processes are so critical to many processes, continued emphasis should be placed on field studies of the turbulent cascade of energy and scalars from the mesoscale down to the micro-scale where molecular dissipation takes place (see Ocean Turbulence chapter). These studies are of intrinsic interest, and they provide the basis for comparison with new numerical studies of these processes (featuring large-eddy and direct simulation approaches to resolve the turbulent flow) and the development of better parameterizations of turbulent mixing. The parameterizations currently used in coastal numerical models are known to have serious shortcomings that reduce their usefulness. Improved parameterizations would benefit both coastal ocean research and the use of models for practical applications (e.g., search and rescue, currents and sea surface elevation for ship routing, fisheries). The continued increase in computing power plus the use of finite-element methods is now allowing coastal models to be built with highly resolved realistic model domains. As this trend continues, model accuracy will become even more dependent on turbulent mixing parameterization. A major improvement in the parameterization will have a very important and wide impact on ocean modeling and interdisciplinary research in general.

- **Improved moorings.** Many advances in physical understanding of the coastal zone have come about through improved moored and shipboard instrumentation that allow more accurate sampling on both short and long time and space scales. With this has come a better appreciation of the diverse roles of physical processes in other coastal phenomena and the local ecosystem dynamics. As a result, and with continued development and use of moored instrumentation in biology and chemistry, we can anticipate major advances in a number of areas, such as (a) biophysical coupling, (b) cross-shelf transport processes, (c) turbulent mixing processes and their parameterizations in numerical ocean models, (d) buoyancy-driven flows and fronts, (e) sediment transport, (f) biogeochemical fluxes and (g) the shaping of water column and benthic communities.

- **Monitor subseafloor processes.** An appreciation of the long-term development of the continental terrace requires a much more complete sampling of this terrace, using an enhanced database of seismic images of the internal structure of the terrace to guide scientific ocean drilling and sampling. These geologic investigations should also incorporate monitoring and study of a host of subsurface processes, including fluid (e.g., groundwater) flow, microbial activity and gas hydrate formation.

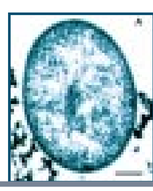
- **Further integrate biology and chemistry.** Carbon is just one important element in the biogeochemical cycling that takes place in the coastal environment. We can take advantage of recent advances in remote sensing, continuous chemical sensing—and the application of tracers to investigate biogeochemical reactions and exchanges in places such as the transient boundary of river plumes and in the permanent mixing zones of estuaries. We need to develop a better sense of how the balance between the supply of major and trace nutrients regulates species composition and ecosystem structure in coastal regions. Stronger integration of organismal physiology into biogeochemical studies will enhance this progress.

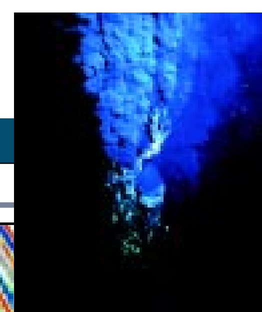
- **Conservation- and restoration-based research.** Building a strong scientific base for applied marine science is fundamental to our ability to manage and conserve marine resources for sustainability. Hundreds of millions of people depend on coastal marine ecosystem goods and services, but we have, at present, only a minimal scientific basis for focusing on the most important locations for conservation, and even less of a basis for effective restoration of damaged systems. However, experimentally based efforts in the restoration of coastal habitats are being undertaken, and the increased numbers of marine protected areas and marine parks make experimental tests of management and restoration efforts tractable over significant spatial scales.

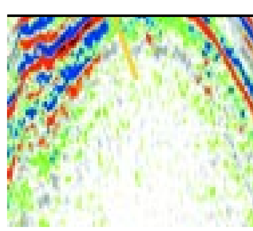
THE OCEAN
BELOW THE SEAFLOOR

Fluid Flow and Effects on Geology, Chemistry and Life in the Crust

Fluid flow through oceanic crust, and through the seafloor along the margins of the ocean basins, is the fundamental process by which mass and energy are transferred from Earth's interior to the ocean and atmosphere. Fluid fluxes through oceanic crust are so large that a volume equivalent to the global ocean is circulated through the seafloor once every ~6.0 m.y.; fluid flux through active and passive margins is very poorly constrained, but is also likely to be large in many settings. Collectively, this vast system of fluid circulation below the seafloor can be thought of as a second ocean—an ocean below the seafloor. We are just beginning to explore this "ocean," determining the forces that drive fluid flow, estimating the mass and energy fluxes, understanding its influence on geological processes, exploring the extent and distribution of biological activity at and below the seafloor, and assessing the impact of these fluxes and biological communities on mineral, chemical and biological resources. This is an exciting new frontier of research in the ocean sciences, and one with enormous opportunities in the coming decade for both new discoveries and fundamental new insight into coupled geological and biological processes in the deep sea.







WHAT ARE THE BIG PROBLEMS?

The following discussion is organized around a series of questions. Running through all of these questions is the fundamental difficulty of resolving the many temporal and spatial scales over which fluid processes occur in the subseafloor. Fluid flow events occur in seconds to minutes (in the case of hydrologic responses to seismic activity) or millions of years (the time required to pervasively alter oceanic crust by hydrothermal circulation). Flow occurs between grains over distances of microns (creating coupled oxic and anoxic microenvironments), through fractures and cracks at scales of meters (transporting heat and solutes) and along tectonic plate boundaries extending tens of kilometers (lubricating fault zones and transmitting abnormal pressures). Different measurements of the same system can result in fundamentally different views of how that system operates. Making the right combinations of measurements and reconciling the different scales of fluid flow are the central challenges to understanding the ocean below the seafloor.

What are the physical boundaries, hydrologic properties and driving forces responsible for the fluxes of energy and mass through the subseafloor ocean?

The physical boundaries and driving forces responsible for fluid flow through this subseafloor ocean are poorly understood. These parameters must be constrained because they allow us to define the magnitude and significance of fluid flow and related processes, and to make better predictions of how these processes may change in the future. For example, the depth to which water circulates in the oceanic crust is not known, but is fundamentally important because crustal alteration results in incorporation of water into mineral phases that are eventually recycled into the mantle at subduction zones. Subduction of volatiles influences processes occurring within the seismogenic zone and the explosiveness of volcanic activity in arcs. Where seismic data have allowed imaging of ridge crest magma chambers, the deeper limit of fluid penetration and high-temperature fluid-rock interaction have been estimated to be 1 to 2 km. But especially along the more extensive and slower spreading ridges, the depth of fluid circulation in the axial region is largely unknown. Observations in deep crustal sections from ophiolites suggest that fluids may penetrate considerably deeper, perhaps 5 km below the seafloor in some places.

The lateral extent of fluid circulation within the crust and how these systems are recharged is also not known. Is fluid recharge rapid and highly localized, perhaps focused along major faults, or is it slower and more diffuse? What is the nature of the subseafloor "reaction zone," a conceptual region where ordinary seawater interacts and exchanges heat and mass with newly-solidified rock, becoming highly evolved hydrothermal fluid? In some areas, recharging fluids appear to travel tens of kilometers or more, perhaps allowing isolated basement outcrops and faults to ventilate large parts of the seafloor. Measurements of driving forces for ridge-flank circulation suggest that they are very small, requiring an extremely good hydrologic connection across long distances. Recent studies suggest that most ridge-flank flow could be focused through a very small fraction of the crust (see Ridge-Flank Circulation box on opposite page). However, the dimensions of the fluid-flow conduits, and how these connections are maintained over large distances and as the crust evolves, is still poorly understood. Heat flow data suggest that advective fluid exchange ends, on average, at 65 m.y., but chemically significant flow may continue until the crust is extremely old. The residence time of hydrothermal fluids in the crust is critical for assessing the ability of these fluids to support microbiological habitats.

Ridge-Flank Hydrothermal Circulation

Contributed by Andrew T. Fisher, University of California, Santa Cruz

Most of the global marine heat flow anomaly (the difference between predicted and observed conductive heat flow, as measured at the seafloor) is found off axis, far from seafloor spreading centers. On average, seafloor younger than 65 m.y. in age is "cooler" than it should be based on a range of lithospheric evolution models. The expected amount of heat is leaving the crust, but much of it is being carried by hydrothermal fluids. Seafloor heat-flow measurements indicate that heat is redistributed locally within seafloor as old as 100 m.y. Thus, hydrothermal circulation may occur within most of the seafloor. Measurements of pore-fluid geochemistry from samples collected in basement and from sediments immediately overlying basement are consistent with this interpretation and have helped us to understand the significance of the ocean beneath the ocean. New discoveries of an extensive subsurface biosphere raise questions about ridge-flank circulation: What forces drive the flow, and how quickly do fluids travel? How far do fluids travel, and at what depths? How long does the process continue, and what are the essential fluxes (fluid, heat, solutes)?

We show results from a series of calculations intended to address some of these questions. On the eastern flank of the Juan de Fuca Ridge, in crust 1.0-3.5 m.y. old, researchers have documented a vigorous hydrothermal system. Seafloor heat flow is considerably lower than predicted by standard conductive models. Heat flow rises as one moves away from the point of sediment onlap, suggesting that cold bottom water enters the crust and flows laterally beneath the seafloor. Coupled numerical models of heat and fluid flow were used to explore the mechanisms and rates of fluid flow suggested by the heat flow observations. A detailed two-dimensional "grid" was constructed, intended to represent permeable upper basement layers sandwiched between layers having much lower permeability, shallow sediments and deeper basement. Fluid flow was initiated first by starting the system in a hydrostatic state, but the fluid flow went the "wrong way," based on heat flow observations (red curve). However, when researchers first forced fluid to travel in the direction indicated by heat flow measurements, then stopped forcing the fluid flow, it continued in this direction because a hydrothermal syphon had been established. The rate of lateral fluid flow then depended on the thickness and permeability of the upper basement layers, several combinations of which provide an equally good fit to thermal observations (black curves and purple dots). In all cases, rates of discharge are rapid, at least meters per year, and flow occurs over distances of 25 km. Direct measurements will be required to determine where and how far fluids actually flow through the seafloor, but these kinds of calculations help to focus questions and future experiments.

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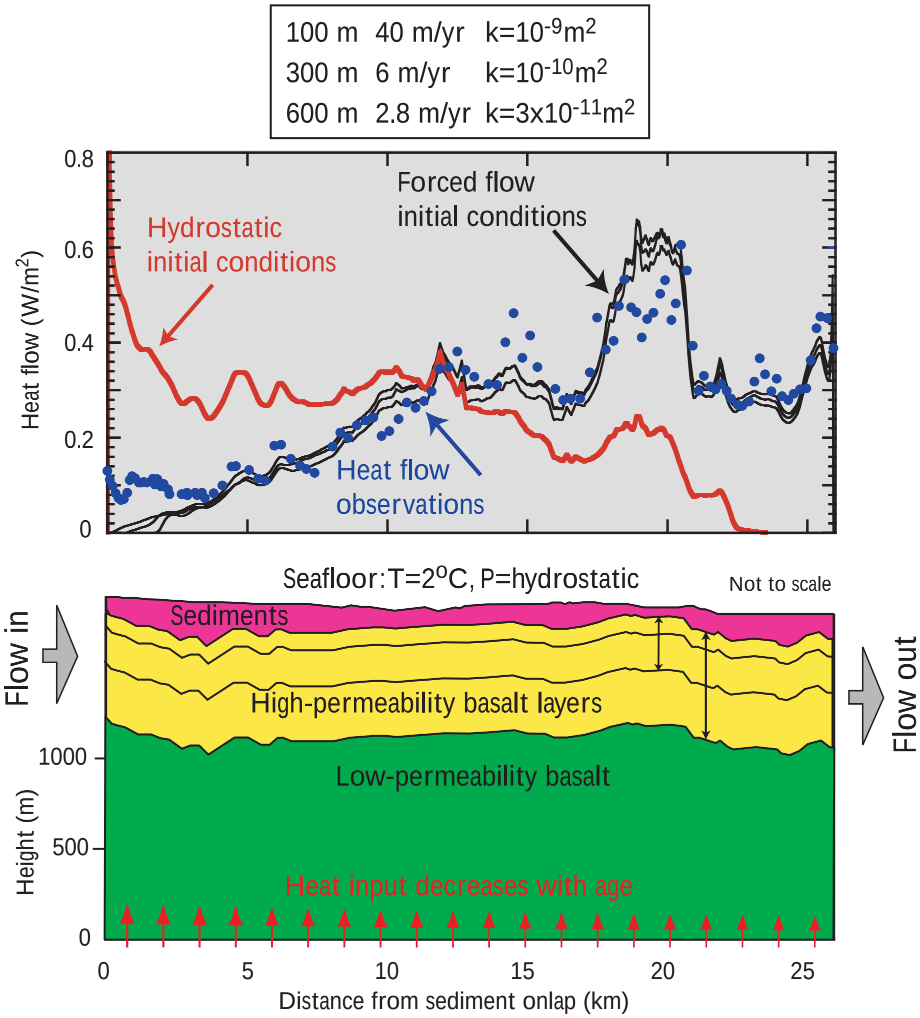


Figure is modified from Stein, J.S., Multiple scale of hydrothermal circulation in the oceanic crust: Studies from the Juan de Fuca Ridge crest and flank [Ph.D. thesis], University of California, Santa Cruz, 2000.

The relative importance of sources and sinks of fluid remains poorly understood at subduction zones. Fluids contained in the subducting basement and sediments, and in the subduction wedge that commonly forms above the trench, are expelled at various depths under the influence of increasing pressure and temperature. The water carried into subduction zones is trapped in the pores of unconsolidated sediment and bound in hydrous minerals. It is released as the sediments dewater and lithify and as the subducted crust dehydrates. Some fluids penetrate into the mantle, influencing global geodynamics and mantle geochemistry.

Fluid venting in many settings has been found to be highly episodic, however, currently we have little understanding of the life cycle of transient events or the fundamental driving mechanisms responsible for them. Fluid flow depends strongly on the permeability of the crust, which is controlled by factors such as grain size, fracture aperture and pore-fluid pressure. These properties are sure to be transient, anisotropic, and highly heterogeneous. Transient fluid expulsion includes hydrothermal venting at ridge crests, cold venting at subduction margins, mud and serpentine diapirism along active and passive margins, gas expulsion leading to pockmarks and slope failure, and diffuse venting in all settings. Understanding the forces driving episodic fluid venting is essential to developing accurate models of coupled hydrological, geological and biological processes of submarine hydrothermal systems.

What is the influence of fluid flow on geological processes at and below the seafloor?

Fluids flowing through the seafloor influence a wide range of geological processes, and these influences feed back into fluid flow. Fluids in fault zones deposit cements, driving permeability down and fluid pressure up. This process may result in brittle failure of the crust, generating a catastrophic increase in permeability. Water carried by the crust into subduction zones influences the strength of the host rock and lubricates seismically active faults. Water carried to greater depths serves as a fluxing agent in the production of mobile hydrous minerals and melt for arc volcanoes. Fluids seeping through sediments in a variety of continental margin settings carry hydrocarbons including methane, which at high pressures and low temperatures, combines with water to form vast accumulations of gas hydrate. And in all subseafloor environments, over a surprisingly broad range of temperatures, pressures and chemistries, the subsurface ocean supports an extensive microbial population comprising the deep biosphere.

Mid-ocean ridges. Some of the most spectacular examples of fluid flow through Earth's crust occur at mid-ocean ridges, where water is driven through and reacts with highly permeable rock. Temperatures are commonly 300° to 350°C and sometimes exceed 400°C. Fluid density contrasts that result in buoyancy-driven flow can be enormous. Driving forces and chemical activity can be enhanced by phase separation, either at sub- or super-critical conditions. Consequences of circulation include rapid exchange of elements and heat between the crust and oceans, deposition of large mineral deposits at the seafloor, and nourishment of unique animal communities at seafloor vents (Figure 17).

One of the fundamental gaps in our understanding of the relationship between fluid flow and geological systems is the influence of ridge-crest hydrothermal circulation on the architecture of oceanic lithosphere. There must be complex feedbacks between energy and mass sources, evolving permeability structure, the distribution of intrusive and extrusive rocks, the importance of faulting, and the stresses associated with seafloor spreading. Which factors dominate heat, fluid, and solute transport at the ridge-crest? Does axial

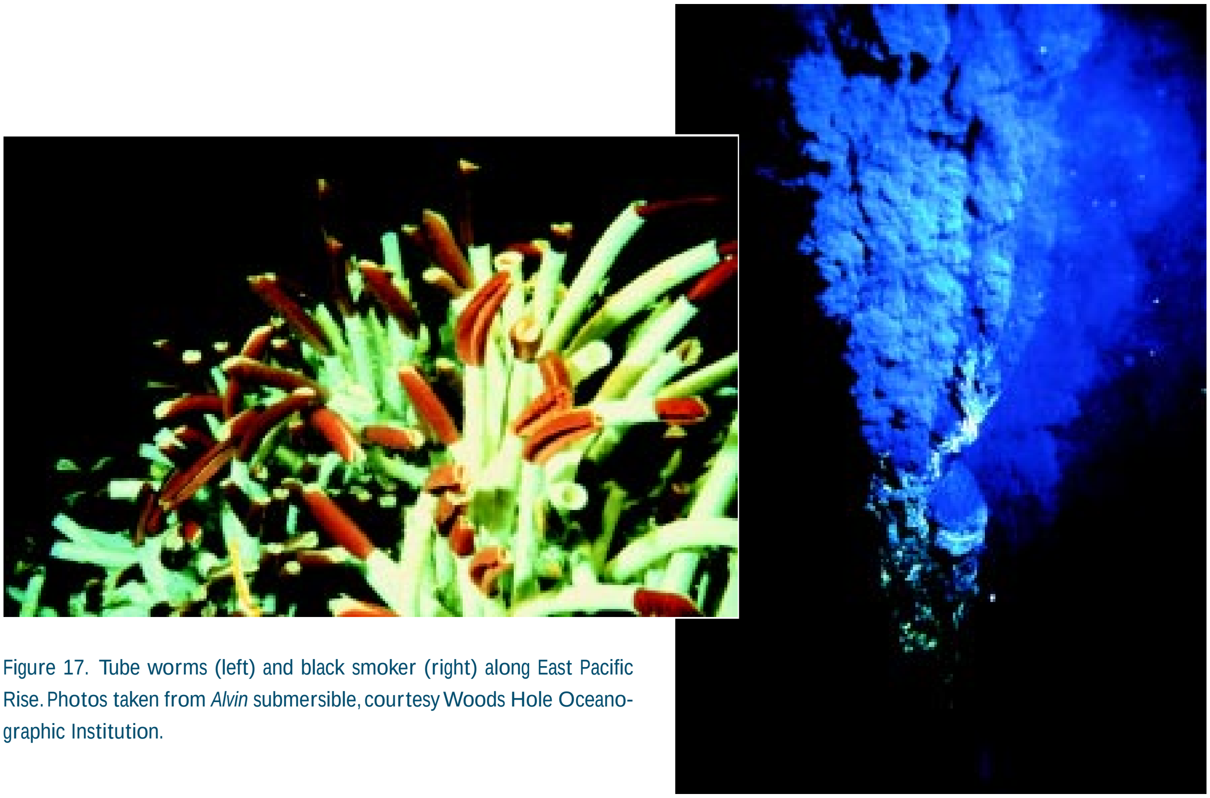


Figure 17. Tube worms (left) and black smoker (right) along East Pacific Rise. Photos taken from *Alvin* submersible, courtesy Woods Hole Oceanographic Institution.

diking play a direct role in focusing high-temperature flows from broad volumes of the crust (required to sustain heat and chemical outputs)? What controls the distribution of vent fields? How do these processes differ at slow-, medium- and fast-spreading ridges?

As the magmatic heat source cools, and as the crust moves away from the dynamic environment of the ridge crest, thermal contraction of the rocks creates stresses and deformation that change permeability and hence the paths of fluid flow. Heat flowing into the base of the plate continues to generate buoyancy-driven flow for millions of years. Complex water-rock reactions result in precipitation of secondary minerals in networks of fractures, while sediment accumulates on the seafloor. The sediment and precipitated minerals restrict fluid flow, producing a highly variable alteration pattern and a progressive change in the thermal structure. Determining the evolution of the thermal structure of oceanic crust and upper mantle as it moves away from the spreading axis is key to understanding the nature of fluid flow within the subsurface, the types of water-rock reactions that occur within different parts of the system, the cumulative impacts of lithospheric alteration, and the nature of subsurface ecologies.

We are beginning to understand the first-order hydrologic architecture of upper oceanic crust on ridge flanks. The greatest permeabilities are found in the uppermost extrusive layer of the igneous crust. Permeabilities are highest in young seafloor. As sediments accumulate, they form a relatively low-permeability barrier to fluid flow. But even where this sediment layer is thick, large parts of the seafloor remain well-ventilated out to 65 m.y. or more. The deeper part of the igneous crust, which comprises dikes, sills, and intrusive rocks, is likely to be much less permeable on average than shallower basement, but faults, fractures, and joints could provide efficient pathways for locally focused flow in some areas. Where deeper flow occurs, it will be very efficient at "mining" heat because the temperature contrast between bottom water and crustal fluids increases with depth below the seafloor.

Rifted and Subducting Margins. Along continental margins, fluids are continuously on the move because of the slow consolidation of sediments transported onto and into the margins. Fluids are also added to the system by the dewatering of subducted slabs in active margins. Generally low permeabilities lead to disequilibrium between production and drainage, and hence to overpressured conditions. Variations in permeability, and in rates of deformation, loading, and fluid production may to lead to large variations in pore pressure and rates of flow. Locally pressures can approach lithostatic levels, and fluid flow can be highly compartmentalized or focused.

At each step, fluid fluxes distilled from the downgoing slab influence fundamental processes. At the shallowest depths, water and carbon fluxes influence the formation and destruction of gas hydrates, and may support a deep, subsurface biosphere as well as the chemosynthetic vent communities observed in forearc regions. At greater depths, excess pore fluid pressures moderate the strength of faults and influence the hazards associated with great earthquakes of the seismogenic zone. At still greater depths the presence of water influences magma production that often results in explosive arc volcanism. Quantifying the significance of fluids in these systems requires that we resolve the magnitude and controls on specific fluxes. Excess fluid pressures, gas hydrate formations and large-scale slope-failure structures have also been identified along passive margins, but we do not know the extent that continental groundwater contributes to fluid fluxes in these settings.

A number of important questions are unresolved. What is the role of water in controlling deformational style at active margins (e.g., ductile vs. brittle; distributed vs. fault-concentrated)? How do chemical fluxes influence the alteration of the margin, and how does this, together with deformation, influence permeability and the relative importance of distributed and fracture-focused flow? How large are fluxes from great depths? How much fluid is returned back to the ocean, and how much is transported to greater depths to serve as a fluxing agent for upper mantle serpentinization and melt production, and ultimately to contribute to mantle heterogeneity? How does lithospheric alteration influence magmatic and volcanic processes above subduction zones? How does water influence seismic rupture, and how do earthquakes influence fluid flow through the generation or release of pore-fluid pressures within the rupture zone, the generation of pressures through ground acceleration, or the generation of permeability? Episodic events, possibly associated with major earthquake rupture and accompanying ground motion, may dominate in some subduction zones. What is the relative importance of transient vs. steady state hydrologic processes?

The hydrologic regimes of passive margins are poorly understood globally, but fluid pressures in excess of hydrostatic are known to influence slope stability in some settings. Margin fluxes influence sediment diagenesis, the shapes of margins by way of mechanical and chemical erosion, the migration and accumulation of hydrocarbons including gas and gas hydrates, and geochemical exchange between the crust and the oceans. At many passive margins, hydrologic regimes may be linked to meteoritic systems on land, with flow driven by topographic head. These systems are extensive, spanning from onshore, across continental shelves, and to continental slopes and continental rises. Critical parameters involving these systems include fluid compositions, sediment/rock alteration histories, lateral pressure gradients, and formation permeabilities.

What are the magnitude, distribution and temporal variability of mass, thermal and chemical fluxes to and from the crustal ocean?

The role of fluids as agents of change is a common thread that links many of the outstanding questions involving the oceanic lithosphere's life cycle, from creation through aging to subduction and entry into the upper mantle. Hydrothermal fluid fluxes are so large that a volume equivalent to the global ocean is circulated through the seafloor once every ~6.0 m.y. Fluxes of fluids and solutes from active and passive continental margins are very poorly constrained, but are likely to be large in many settings. Collectively these fluxes (coupled fluid, heat, mass) and associated chemical reactions between seawater and oceanic rocks lead to fundamental interactions between the lithosphere and the overlying ocean. One critical goal of active margin research is to determine the budgets of volatiles such as water, methane and carbon dioxide, as they enter, traverse, and exit subduction zones. Subduction carries water and other volatiles to progressively higher pressures and temperatures.

Alteration budgets for the crust and upper mantle need to be quantified at all stages of the life cycle of an oceanic plate, from its birth at a spreading center to beyond the time at which the plate is subducted, over the full range of spreading rates and in various sedimentation regimes. The cycling of seawater through the ocean crust and mantle must be understood in terms of global cycles of water, carbon, oxygen, metals and other elements. These fluxes also need to be resolved in terms of specific lithospheric properties. For example, the rates of cycling at mid-ocean ridges should depend fundamentally on plate spreading rates. As oceanic crust ages, early high-temperature alteration can be overprinted by lower temperature reactions. These processes likely lead to a crustal section that is extremely heterogeneous in its mineralogy and chemical composition.

Water-rock reactions that result in black smoker fluids (Figure 18) emanating from the seafloor are thought to occur in relatively shallow circulation systems driven by magmatic heat sources. A great deal has been learned about crustal alteration through sampling of vent fluids and upper crust and by experiments and

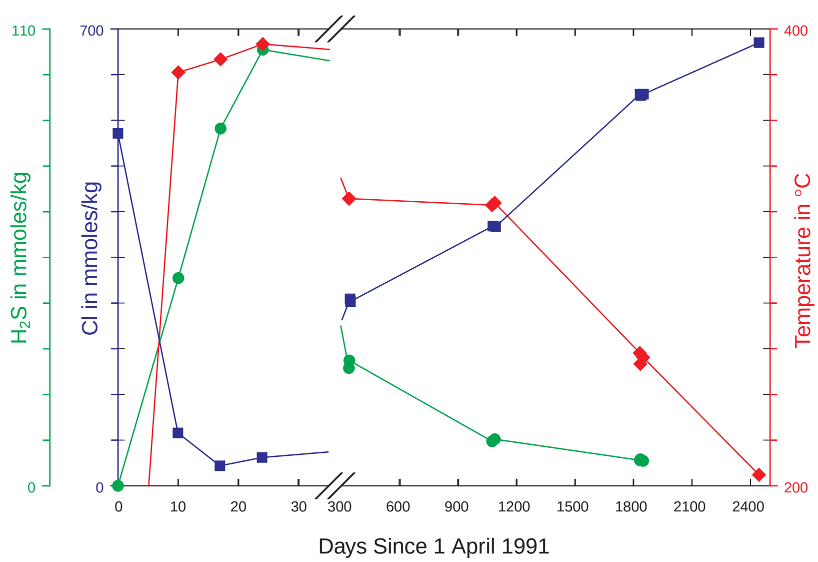


Figure 18. Plot of temperature, Cl and H_2S from hydrothermal vent "A" at 9°46.5'N along the East Pacific Rise. A volcanic eruption had occurred at that site just prior (weeks at most) to diving with *Alvin*. Data are from the period April 1, 1991 through December 1997. Note the dramatic chemical changes that occur in the vent fluid compositions following the volcanic eruption; the system had not yet stabilized nearly seven years later. The value on the y-axis is the seawater value for reference, where appropriate. The low Cl and high H_2S early on reflect the vapor phase nature of these fluids. With time, the Cl gradually increases and the temperature and H_2S decrease. Data are from Von Damm, K.L., S.E. Oosting, R. Kozlowski, L.G. Buttermore, D.C. Colodner, H.N. Edmonds, J.M. Edmond and J.J. Grebmeier, Evolution of the East Pacific Rise hydrothermal vent fluids following a volcanic eruption, *Nature*, **375**, 47-50, 1995, and from Karen Von Damm, University of New Hampshire (unpublished).

modeling. Based on these studies, a model has been developed that predicts the types of alteration reactions and resulting elemental exchanges between fluids and rocks from the time seawater enters the crustal section until it discharges at high-temperature hydrothermal vents. The true nature of the reaction zone (the conceptual region where fluids develop their chemical signatures through high-temperature reactions and the metals that ultimately are concentrated at the seafloor in massive sulfide deposits are extracted), however, is unknown. The lack of samples from these depths has limited our ability to understand processes such as phase separation and the speciation of solutes and metals in fluids along the transport pathways. In addition, recent tantalizing evidence of microbial activity in rock samples suggests that bacteria may play an important role in crustal alteration. Fluid fluxes on ridge flanks have been estimated to be five to ten times larger than those on ridge crests, but the chemical impacts of ridge-flank circulation are very poorly constrained. Some ridge-flank fluxes rival riverine sources or sinks in magnitude, but others are completely unknown.

What is the extent and distribution of biological activity within the crust and where the crustal and blue oceans meet?

The existence of a subseafloor biosphere is intimately tied to fluid flow. Fluids cycle nutrients, provide heat and may contribute to physical transport of genetic material within sediments and basement rocks. The extent of Earth's deep, subseafloor biosphere and the character of the "extremeophiles" populating it, however, are largely unexplored. Initial results from scientific ocean drilling indicate that microbial ecosystems thrive in both oceanic crust and in deep (more than 750 m), subsea sediments—regions thought to be barren only 10 to 20 years ago (Figure 19). The discovery of novel microorganisms and metabolisms in the subseafloor operating in physical isolation from the more highly evolved organisms and mechanisms in the overlying ocean has opened up an exciting new frontier of research.

The need to examine subseafloor microbial ecosystems more closely is a priority. Studies of microbial populations, pore-water chemistry and organic-chemical composition over ranges of sub-bottom depths in different tectonic settings will enhance our understanding as to how and to what extent the deep biosphere takes part in global biogeochemical cycling. Drilling in hydrothermal discharge zones (both focused and diffuse) will provide needed samples from a wide range of temperatures over relatively short distances. Exploration of subduction zones will elucidate bacterial involvement in the remobilization of materials from descending plates and about responses of communities to fluids migrating from greater depths. Examination of microbial populations around seafloor mud mounds and other sites of hydrocarbon-related diagenetic activity will provide information about the role of bacteria as sinks for fossil fuels. Studies at methane-hydrate boundaries will provide information about the long-term stability of such deposits and about global budgets for greenhouse gases. Carbon and redox budgets for the deep bacterial community are completely unknown. If microbial communities within sediments intercept reduced substances ascending with fluids from the sediment-hard rock interface, this process could have substantial effects on climate and atmospheric composition.

Macrofauna clustered around vent sites are now being characterized (focused/diffuse, hot/warm/cool, long-lived/short-lived). Nearly every new vent field adds to the catalog of previously unknown species (and sometimes, genera), whose relations to known animals are poorly understood. How do vent communities colonize

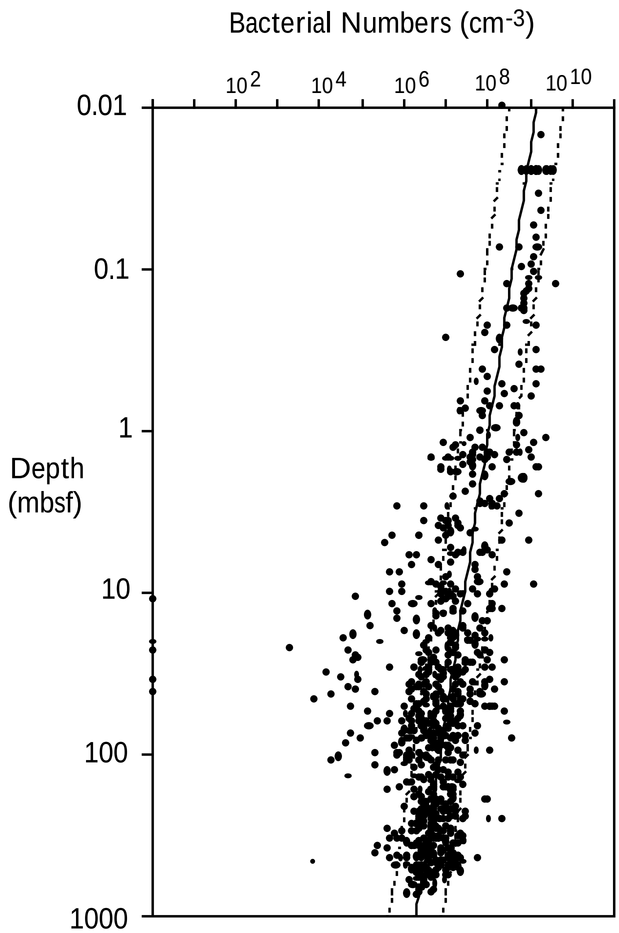


Figure 19. Bacterial abundances as a function of subbottom sediment depth as seen in ODP boreholes down to ~ 750 mbsf. Figure reprinted with permission from Parkes, R.J., B.A. Cragg and P. Wellsbury, Recent studies on bacterial populations and processes in subseafloor sediments: A review, *Hydrogeol. Jour.*, **8**, 11-28, copyright Springer-Verlag, 2000.

new discharge sites (see Figure 11 on page 76)? How are their larvae transported across vast distances? How do they derive nourishment during periods when they are between vent sites? Why are these some species found at more than one kind of site and others that are extremely restricted (spatially, temporally)?

Subseafloor fluid sampling may allow the discovery of organisms that will extend the accepted temperature and pressure limits of life or prove more ancient phylogenetically than those currently known. The possibility of primitive cellular groups or physical arrangements in which genetic information is freely exchanged to accomplish the metabolism of what would normally be considered an individual organism has been postulated for subsurface refugia but not taken beyond the speculative phase. In serving as physical substrata (and even nutritional substrates) for the formation of microbial mats and stably close associations between cells, the abundant mineral surfaces that characterize the crustal ocean could stabilize or facilitate genetic exchange as it is understood to occur between modern organisms and envisioned to occur between more primitive cells.

Recognition of the crustal ocean as a potentially vast and unexplored extension of the known biosphere, and provision of suitable facilities to explore it, provides unprecedented opportunity for modeling and experimental ventures into the realm of the origins and early evolution of life on this planet and possibly elsewhere. The hypothesis that life originated at hydrothermal vents has been with us for two decades; a general consensus on the merits of the idea has been reached. Next to come will be dedicated conceptual and experimental tests of the hypothesis, based on new information emerging from interdisciplinary studies of the crustal ocean. On-axis study at hydrothermal vent sites will be essential, as extensive hydrothermal activity is believed to have dominated the Archean ocean (see Deep Biosphere box on opposite page). But the importance of the rest of the contemporary crustal ocean—extensive off-axis zones, sedimented regimes and basaltic glass—cannot be underestimated. These areas also provide permissive conditions for the evolution of life and its chemical precursors, as well as a refuge from modern processes, from predation by highly evolved organisms and enzymes to irradiative assault that would otherwise erase the existence of primitive organisms or consortia on this planet. They also may best resemble crustal zones on other planets (Mars) and moons (Europa), where much speculation ensues regarding the possible existence or fossilization of microbial life. Study of Earth's crustal ocean is now seen as the best option available to the scientific community for unraveling the mystery most central to humankind—the origins and early evolution of life.

What are the impacts of fluid fluxes and subseafloor communities on mineral, chemical and biological resources?

Polymetallic sulfide deposits are found on mid-ocean ridges, on axial and off-axis volcanoes and seamounts, in sedimented rifts adjacent to continental margins and in subduction-related backarc environments. Land-based massive sulfide deposits and those found on the seafloor are products of the same geological and geochemical processes, and many analogies can be drawn. The discovery of ore-grade gold deposits in a submarine caldera (Miyouin Knolls in the Izu volcanic arc) and active submarine Kuroko-type iron formation (Panarea in the Aeolian arc) are exciting examples of the economic potential associated with subseafloor fluid flow that is just being recognized.

While the economic potential of seafloor hydrothermal deposits is difficult to assess without a better understanding of their distribution, size and bulk composition, these modern, actively forming seafloor deposits are excellent natural laboratories for understanding the genesis of volcanogenic massive sulfide deposits. A major advantage of the study of modern seafloor hydrothermal systems is that the composition of the end member ore-forming fluids can be measured—a prerequisite for geochemical modeling and mass balance calculations. Furthermore, detailed studies of the regional setting and geochemistry of seafloor deposits can identify important tectonic and petrologic controls on the occurrence of economically more attractive (e.g., gold-rich) massive sulfide deposits in the geologic record. This knowledge can be applied directly to identify promising tectonic settings for land-based mineral deposit exploration.

Organic carbon is an important component of the subseafloor ocean. It supports much of the life there and migrates through the fluid flow system as a medium of energy exchange. In its migration it is occasionally trapped and accumulates to form economically important energy resources. In other settings it escapes to the ocean and the atmosphere where it may, under the right conditions, cause sudden, large (4° to 7°) increases in global temperatures (see Global Warming box on page 28). The oil exploration industry has concentrated its research efforts on discovering the concentrated source beds capable of producing large volumes of hydrocarbon fluids and on determining how these fluids migrate through and are trapped within the subseafloor ocean. There is still much to be learned about the basic rates of gas and oil production through both physical and biological processes and of the constraints on its movement through and out of

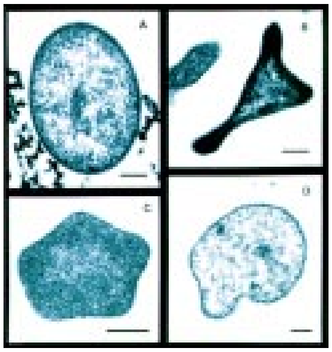
The Hot, Deep Subseafloor Biosphere

Contributed by Jody Deming and John Baross, University of Washington, Seattle

Direct evidence for a potentially vast biosphere in the "ocean below the seafloor" continues to accrue from deep-sea drilling cores and oil wells. But the more dynamic subseafloor environments most likely to provide suitable habitats for microbial growth and evolution are those that have so far evaded direct sampling—the near-ridge hydrothermal regions. Scientists have nevertheless combined a wide range of measurements to model these zones from a microbial perspective and predict how organisms may respond to submarine diking-eruptive events that disrupt the rocky seafloor. Recent eruptive events in the Northeast Pacific have allowed for sampling of the event plumes that emerge into the overlying ocean, with the resulting discoveries of novel microorganisms that can be traced by their characteristics to a subseafloor origin (Figure left).

The model depicts stable, non-eruptive periods (Figure right, A), as characterized by gradual subseafloor gradients in temperature and chemistry through highly porous (up to 36%) and permeable zones. These subseafloor conditions provide for the maintenance and growth of microorganisms dependent on moderate temperatures (mesophiles) and high temperatures (hyperthermophiles). During an eruptive event (Figure right, B), zones of microbial life are disrupted dramatically, exposing all thermal classes of the organisms to much harsher thermal and chemical conditions, ultimately flushing them from the subseafloor, sometimes within a matter of hours. As a result of the harsher conditions, volatiles and other sources of energy are extracted progressively from the fresh rock (Figure right, C), later fueling a wide range of microorganism metabolic types (Figure right, upper right panel) as they resettle in both shallow, cooler aerobic habitats and deeper, warmer anaerobic zones. Over time, the system returns to initial conditions (Figure right D), but before again reaching those stable conditions, high concentrations of ejected hyperthermophiles are predicted as a result of the initial flushing of the system and secondary blooms within it (Figure right, E).

The ready detection and successful cultivation of strictly hyperthermophilic microorganisms from the event plumes of eruptions has been interpreted as strong evidence for a hot, deep biosphere along ridge-spreading zones. Because these microorganisms can only grow at minimal temperatures of 50°C (and to maxima often well above 90°C), they could not have developed in the event plume itself (typically at near-bottom water temperatures of less than 4°C). Negative results from samplings of surrounding oceanic habitats leave only the hot zones deep in the subseafloor as home to these hyperthermophiles. A model event-plume hyperthermophile, an Archeon known as GR-1 (Figure left, A) and currently under intensive study, lives a metabolic lifestyle in the laboratory that would make it highly competitive in the subseafloor. It is less dependent on complex organic compounds than seafloor organisms and uses volcanic volatiles to achieve optimal growth. It also uses electron acceptors present in basalt, reducing ferric iron to ferrous iron in the form of magnetite. These unique traits are reflected in its phylogenetic position outside of the well-known hyperthermophilic genera of *Thermococcus* and *Pyrococcus*, making it a new genus and prime candidate for further modeling exercises of subseafloor habitats near ridge-spreading zones. Studies of such novel hyperthermophiles provide great promise for understanding the nature and extent of the subsurface biosphere on Earth and perhaps elsewhere.



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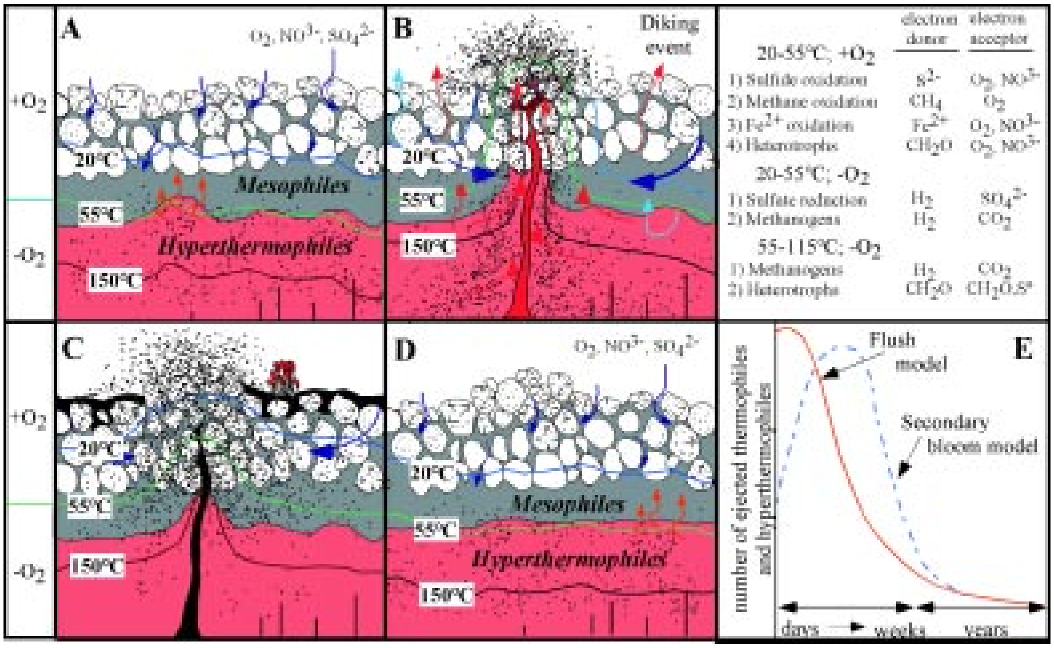

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the subseafloor. The continued movement of oil exploration into deeper waters, where little data exist on either the source beds or the reservoir rocks, affords the academic research community an opportunity to develop new partnerships with this industry. There are shared interests in the organic source, the rates of production and degradation, the rates of migration, migration pathways and the ultimate fate of organic matter in the subseafloor system. Seismic images of the subseafloor world acquired by industry will point the way for exploration of this realm. Technology developed by industry will aid us in sample recovery. In turn, our basic research on the processes which create, alter and move hydrocarbons will be of direct benefit to the exploration industry.

Enormous quantities of hydrocarbons are stored in deep marine sediment as solid gas hydrate and free gas bubbles (see Gas Hydrates box on opposite page). This ocean carbon reservoir may contain 15 to 20 times more carbon than the entire terrestrial biosphere. Marine gas hydrates are not concentrated exclusively in layers, but are found mostly dispersed in sediment pore space and are distributed over thousands of square kilometers in considerable water depths. The economic potential of gas hydrates, as well as the technical feasibility of their extraction, is unknown. In addition, it is increasingly apparent that gas hydrates play a role in the cycling of carbon on Earth's surface, and the stability and movement of gas hydrate is greatly influenced by fluid flow. Gas hydrates may be a future energy resource, a catalyst for mass wasting on continental margins and also a substrate for an unique subseafloor biosphere.

Before the discovery of the subseafloor biosphere, bacteria isolated from hydrothermal environments had already made a big impact on biotechnology, for example in providing enzymes for the polymerase chain reaction that has galvanized molecular genetics. Some hydrothermal bacteria can not only just survive but also are biochemically active at temperatures up to at least 120°C and there may be bacteria able to be active at even higher temperatures. This is significant because it suggests that bacteria are likely to be present several kilometers beneath seafloor. In addition, bacteria may be involved in the formation of fossil fuels at depth as the "oil window" occurs between 100° to 150°C and large bacterial populations emerge with production fluids from some oil reservoirs. It also looks likely that the deep biosphere will provide an even more diverse source of bacteria than the hydrothermal environments and as a result have a much greater scientific and biotechnological impact.

As more is discovered about the organisms and metabolic processes that occur in the crustal ocean and at its mixing interface with overlying seawater, new biological and molecular resources for society will emerge. Confidence in this prediction comes from recent success along these lines: microorganisms cultured from hydrothermal vents have yielded enzymes and processes already on, or under development for, the biotechnology market. DNA-modifying enzymes from hyperthermophilic Archaea discovered at hydrothermal vents are now produced and sold commercially. Industrial investment in identifying additional high-temperature catalytic enzymes from hyperthermophilic microorganisms for the engineering of specialty chemicals remains high. The tolerance of >5 mM concentrations of cadmium and parallel precipitation of the metal by a mesophilic vent bacterium has drawn attention to the organism as a prime candidate for bioremediation applications. The significant ongoing exploration of the ocean for metabolic byproducts of medical interest (new classes of antibiotics and other pharmaceuticals) will logically be extended to the ocean's subsurface, as increasing numbers of subsurface organisms and genes become available for byproduct screening.

Burning Ice: Gas Hydrates from the Ocean Floor

Contributed by Marta Torres and Anne Trehu, Oregon State University

Gas hydrates resemble compacted snow, contain large amounts of natural gas, and occur at many places under the ocean floor including Oregon's continental slope. These unusual solids consist of "cages" of water molecules that trap methane and other gases, which originate from the decomposition of organic material in ocean sediments. Gas hydrates form in the temperature and pressure conditions common on continental margins; thus the locations of known or inferred gas hydrates are worldwide.

Gas hydrates from continental margins are receiving significant scientific and economic attention because they could be of major societal relevance. While the total energy reserve stored in gas hydrates is still poorly known, they may comprise the largest fossil fuel reservoir on Earth. In addition, Methane is a potent greenhouse gas and the release of the large volumes stored in hydrate deposits owing to decreases in ocean depth (causing a decrease in pressure) or increases in temperature may significantly influence the global climate. Recent studies, for example, suggest that gas hydrates may have contributed to some of the past episodes of global warming recorded in Earth's geologic history.

A spectacular massive methane hydrate deposit off the coast of Oregon has recently been the focus of research by an international team of investigators from the US, Germany, Canada and Japan. At this site, known as Hydrate Ridge, methane hydrates are located at the seafloor as well as in the subsurface. Massive carbonates formed from oxidation of methane are also present and record past hydrate dissociation. This site lies less than 50 miles west of Newport, OR, making it very accessible for repeated detailed studies. Very large quantities of gas hydrates are also exposed on the seafloor in the Gulf of Mexico on the Mississippi shelf. They are formed from the upward migration of fluids saturated with methane and other trace gases and have been observed to be unstable with the passage of warm water eddies. From the ubiquitous seismic evidence of gas hydrates on continental shelves world wide we may expect to find more examples of such sites.

Long-term goals are: (1)to understand the geology of the system, (2) quantify the amount of methane present (3) measure the energy and chemical fluxes associated with the hydrates and (4) evaluate the impact of methane hydrates on the marine environment. Seismic imaging has revealed widespread hydrate and gas in the subsurface and a complicated plumbing system bringing fluids to the seafloor. Current and planned research includes measuring chemical and fluid fluxes at the seafloor and drilling by ODP, and using other platforms to calibrate remote sensing techniques and document subsurface biogeochemical processes. Further progress will require development and implementation of new technology to permit retrieval of gas hydrates at *in situ* conditions and long-term, real-time observations of geophysical, geochemical and biological processes.

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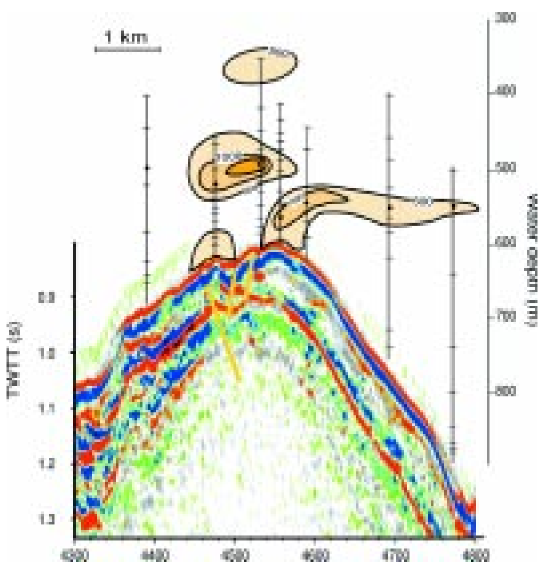

Methane plume in lower water column resulting from gas discharge at the seafloor. Seismic reflection line across northern summit of Hydrate ridge. Subsurface reflection parallel to the seafloor indicates the widespread presence of hydrate.

Because of the large amount of methane in gas hydrates, they have been called "burning ice."

WHAT MAKES PROGRESS POSSIBLE NOW?

Recent technical advances that have made possible the detailed exploration of the seafloor have been accompanied by investigations of the ocean below the seafloor. There has also been a serendipitous confluence of technical capabilities, scientific interest and public curiosity about ocean environments, and a new realization that the ocean below the seafloor must be better understood in order to address a wide range of questions. The early stages of this new wave of exploration began about 20 years ago with the discovery of large benthic communities surrounding hydrothermal vents. Similar communities were found on continental margins. Simultaneous developments in ocean drilling technology allowed selected crustal environments to be drilled, sampled, examined and actively measured. Several large seismic events along active margins, and documented relationships among fluid flow, fluid pressure and earthquakes have demonstrated the importance of understanding linkages within the seismogenic zone. Significant progress in understanding fluid transport in systems with varying porosity and time scales has been detailed in the oil reservoir and hydrological literatures, providing a wealth of insights available for transfer to those studying the complex oceanic subsurface. Growing understanding of the potential influence of gas hydrates on global carbon budgets, and their role in climate change, has sparked additional research efforts. Public awareness of the importance of these relationships is growing.

Additional technical advances came in the form of computing (both hardware and software), communications, video, sampling and submersible technology. Finally, we are beginning to establish long enough records (observational and sampling) at individual sites so that we can begin to document the dynamic behavior of complex fluid-rock systems. Some of these observations have come from repeated visits to sites so that they could be photographed and sampled, but other critical results have come from temporary and more permanent seafloor observatories (see CORK box on opposite page). It is as if hydrologists had been limited to observing and sampling the Mississippi River once or twice a year, but suddenly were permitted to monitor the river constantly, to evaluate its flows, observe responses to rain events and urbanization, record fluid chemistry and survey biological communities. The overarching realization is that fluid flow and associated processes and properties are inherently transient and interdependent, requiring a new approach to resolve fundamental problems. Detailed, multidisciplinary, continuous, active and passive experiments are required to understand the dynamics of complex geological systems, and the oceanographic community is now prepared to undertake these kinds of experiments. The study of the subseafloor ocean is about to take a quantum leap forward.

CORK Subseafloor Hydrogeological Experiments

Contributed by Keir Becker, University of Miami and Earl E. Davis, Geological Survey of Canada

Fluid circulation in subseafloor formations profoundly affects a wide range of Earth processes. Hydrothermal circulation controls heat and chemical balances and possibly subsurface microbiological communities in young oceanic crust. Dewatering in subduction settings is intimately related to earthquake cycles and carbon cycling. Utilizing boreholes to understand these hydrogeological systems *in situ* by direct sampling and borehole experiments has long been a key goal of the Deep Sea Drilling Project and the Ocean Drilling Program. DSDP/ODP holes left open to the oceans—the typical case through 1991—provided hydrological shunts to the natural circulation systems, in essence presenting perturbation experiments. In some cases the downflow of ocean bottom water into the hole can be used to constrain natural conditions. More often, however, drilling-induced circulation that can persist for years in open holes completely obscures natural processes.

To effectively use boreholes as *in situ* hydrological laboratories, then, requires sealing them to allow recovery from drilling-induced perturbations. This need motivated development of the CORK (Circulation Obviation Retrofit Kit) hydrogeological observatory (Davis et al., 1992). From 1991 to 1997, several CORKs were successfully deployed in settings where a hydrogeologically active formation was overlain by a less permeable formation. Each CORK corresponded to a natural seal and allowed reestablishment of equilibrium conditions and processes in the subseafloor formation. The installations have been revisited with manned or unmanned submersibles months and years after deployment for recovery of pressure and temperature data, reprogramming, and installation of long-term fluid sampling and microbiological filtering experiments (see photo).

A new generation of "Advanced CORKs" will be able to seal multiple zones in a single hole, more closely corresponding to natural hydrogeological structures and opening new opportunities for subseafloor hydrogeological observatories (see diagram). The new designs will allow deployment of an enhanced range of long-term instrumentation, with configurations specifically tailored to study microbiology, gas hydrates or seismogenesis in addition to more standard temperature and pressure monitoring. The initial deployments for two distinct engineering approaches to such multi-seal installations are scheduled for 2001. Two wireline instrumented multi-packer systems or "Wireline CORKs" will be installed in Holes 504B and 896A on the southern flank of the Costa Rica Rift utilizing Scripps Institution of Oceanography's wireline Control Vehicle. A few months later, the first ODP "Advanced CORKs," or instrumented multi-packer casing systems, are scheduled to be installed during ODP Leg 196 at two sites in the Nankai Trough in the western Pacific.

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THE CORK IN HOLE 1026B
REENTRY CONE AND CORK DEPLOYED JULY, 1996, LEG 168
MICROBIOLOGICAL FILTERING COLUMN DEPLOYED OCTOBER, 1997
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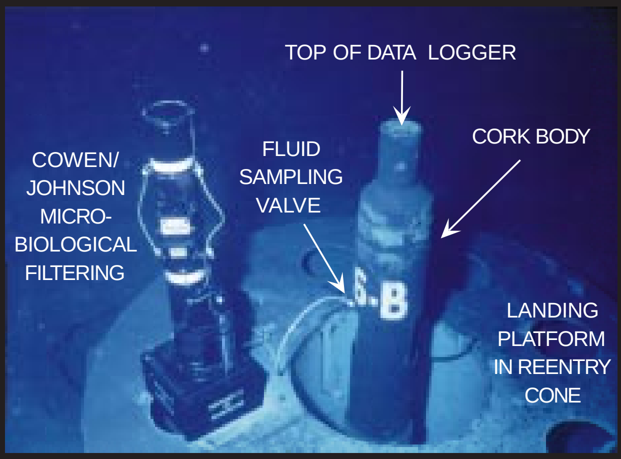

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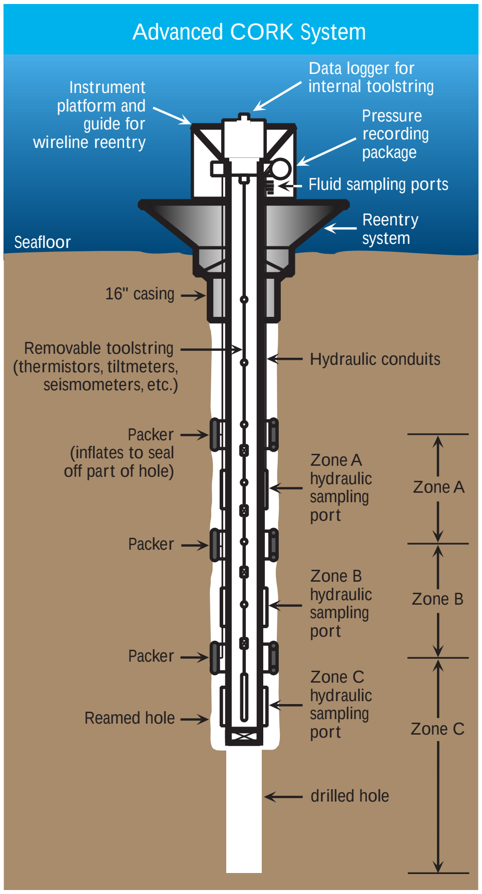


WHAT IS REQUIRED FOR PROGRESS?

The discovery of the fluid realm within the seafloor was based on a new paradigm for Earth behavior and evolution (plate tectonics) and the development of new technology for Earth monitoring (mapping, submersibles, drilling, instrumentation). Our understanding of the dynamics of fluid flow within oceanic sediments and basement will depend in the future on our technical ability to image, sample, monitor and model complex systems. To image the ocean floor and the subseafloor in great detail and monitor the ocean just above the seafloor over wide regions will require development of, and access to, sophisticated seafloor mapping techniques, submersibles and remotely operated vehicles, as well as automated underwater survey vehicles. Subseafloor imaging is needed to describe the physical setting of the subseafloor ocean and to properly site detailed sampling efforts, from the scale of meters to kilometers, down to nanometers to millimeters, the scale relevant to a microbe's size.

We have sampled the subseafloor ocean where it exits the crust in hydrothermal plumes, but to understand its circulation within the crust, we must drill through the overlying sediments and into the crust itself. We need to penetrate into several critical environments, but drilling, sampling, testing and monitoring technology requires improvement before the entire seafloor is accessible. Working on young-crust, bare-rock systems remains extremely difficult. Drilling holes deeper than about one kilometer into the seafloor is challenging in any setting because debris from drilling and cavings from the walls of the hole tend to clog drilling tools. Riser drilling will be needed to penetrate deep into the oceanic crust and tap the very region where earthquakes occur in subduction zones. Once holes are drilled and cased, borehole and seafloor observatory technologies will be needed to power, monitor and test these installations, and to record and communicate results to surface ships and to shore. The development of two-way communications, power and control networks will bring in a new era of direct experiments and passive monitoring of detailed time-series dynamics both at and within the seafloor.

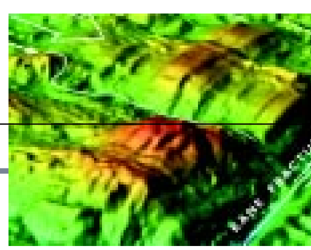
Making sense out of the large amounts of data sure to accompany the new era of exploration and testing will require two additional developments. First, we need to learn to manage (store, access, cross-reference) large data sets so that they are accessible to a broad community. This will allow truly collaborative, international, interdisciplinary science to be accomplished. Second, we need to learn to apply sophisticated coupled models to help us interpret the new samples and data that will be collected. In some cases, this will require development of new codes and solution techniques, but in other cases, it will require mainly that scientists take a broad, open view of the observations, and apply basic concepts to a range of temporal and spatial scales.

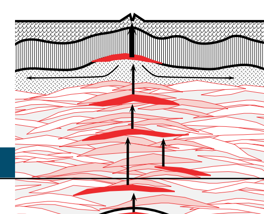
DYNAMICS OF OCEANIC LITHOSPHERE AND MARGINS

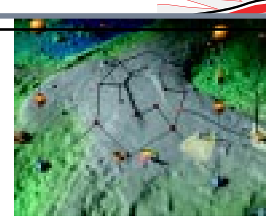
One of the great accomplishments of the plate tectonics revolution forty years ago was the recognition that we live on a dynamic planet. Earth is changing on a variety of temporal scales, from the millions of years required to open and close ocean basins or form mountain ranges to the few seconds it takes for a devastating tsunami-generating earthquake or explosive volcanic eruption to completely alter the local landscape. These geologic processes have a complex, and still poorly understood, influence on the biosphere, hydrosphere and atmosphere.

The interaction of ocean crustal processes with the ocean itself takes place through the cycling of sea water through the crust. The physical, chemical and biological impact of this cycling is the primary focus of the preceding theme chapter. Here we focus on the solid crust itself, its tectonic interactions with the continents, and its recycling through the mantle back to the crust's surface as volcanoes and newly formed seafloor.

Plate tectonics provides a very powerful, quantitative framework for study of the "solid Earth cycle" depicted in Figure 20. In the 1970s and early 1980s, a major focus of research in the marine geosciences was the use of this new paradigm to investigate the kinematics of plate motions, and to explore the first-order geological implications of the plate tectonic cycle. Thus, regional-scale bathymetric and magnetic studies were carried out and used with satellite gravity maps to reconstruct the spreading history of all the major ocean basins over the past 200 million years. Models of the thermal evolution of the oceanic lithosphere were developed that successfully predicted the variation in seafloor depth with age, as well as the subsidence history of rifted continental margins. Plate reconstructions helped to investigate the relative motions of hot spots and to explore the consequences of plate motions on continental tectonics, from the evolution of the San Andreas Fault system in western North America to the uplift of the Himalayas.







Over the past two decades research has expanded significantly from these large-scale kinematic studies to include investigations aimed at understanding specific magmatic, tectonic and hydrothermal processes involved in the solid Earth cycle. There has been a major effort to understand the formation of new oceanic crust through detailed studies at a few specific locations along the mid-ocean ridge. Other investigations have focused on the relationship among seismicity, strain and fluid flow in subduction zone accretionary wedges, and on the early rifting history of continents. Still other work is probing deeper, trying to address questions such as the origin of oceanic hot spots, the ultimate fate of subducted slabs, and the general coupling of processes in Earth's convecting mantle with the overlying lithosphere and the underlying core. With this increased emphasis on "processes" and "dynamics" has also come a greater need for interdisciplinary approaches integrating geophysics, geology, geochemistry and biology into comprehensive, longer-term investigations. Increasingly, the panoply of volcanotectonic provinces (e.g. spreading centers, mid-plate volcanoes and continental margins) are being viewed as part of a single, dynamic "solid Earth system." As a consequence, the distinction between traditional subdisciplines such as "ocean science" and "Earth science" is blurring, with a greater focus on understanding these processes on a planetary scale.

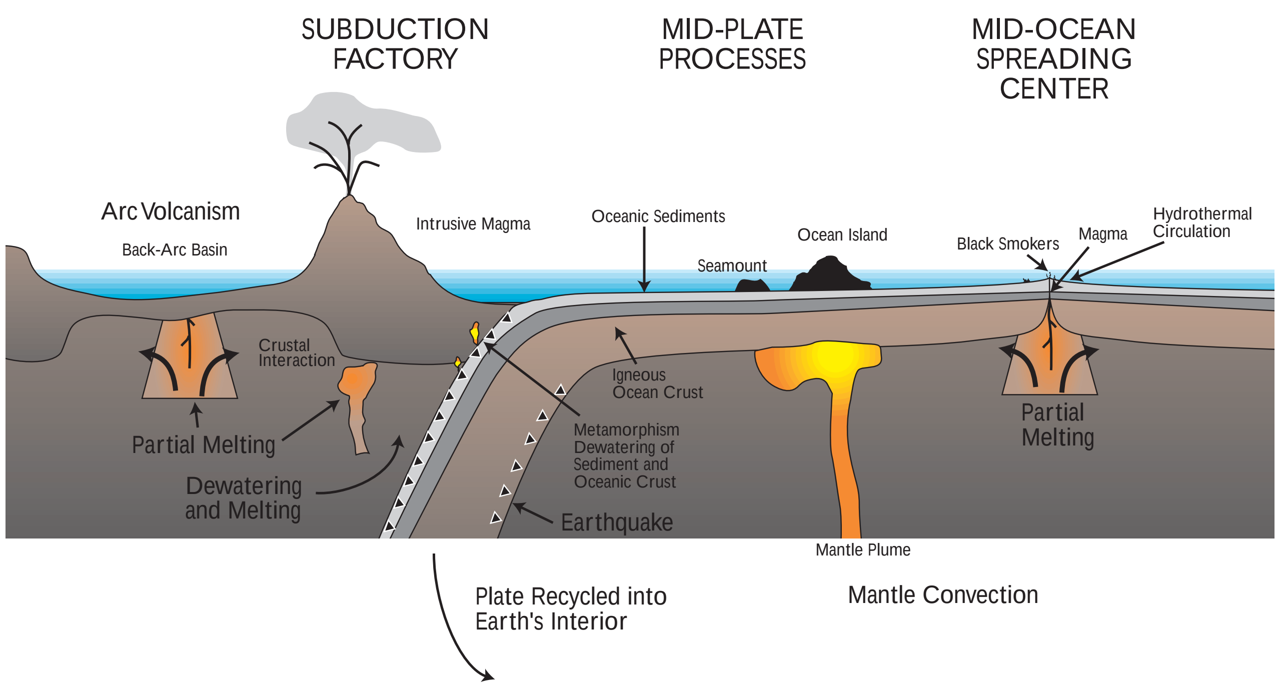


Figure 20. Schematic drawing of the solid Earth's plate tectonic cycle, divided into three major tectonic components: plate creation at mid-ocean spreading centers, modification of the plate as it traverses the mantle, and subduction of the plate and creation of new crust at the convergent margins.

WHAT ARE THE BIG PROBLEMS?

In this section we highlight five areas of research that can contribute significantly to fundamental, and long-standing, questions in geodynamics. These include (1) determining the role of oceanic lithosphere and mantle plumes in the circulation and compositional evolution of Earth's mantle, (2) developing a general theory for melting and mantle transport processes in the oceanic crust and mantle, (3) testing the ophiolite model by drilling the first complete oceanic crustal section, (4) investigating the mechanisms and controls on lithospheric deformation and faulting by studying active seismogenic zones, and (5) determining the time scales of magmatic and tectonic processes operative in the oceans through the establishment of long-term seafloor observatories. In each case we believe the opportunity exists for significant advances, even breakthroughs, in our understanding of these problems over the next decade.

Crust-mantle circulation system

Processes that create and modify the ocean basins play a central role in altering the composition and physical behavior of the mantle. The first stage of this process is the chemical depletion of the upper mantle, producing oceanic crust at mid-ocean ridges. Chemical and thermal heterogeneities formed on the spreading ridges and during tens of millions of years of lithospheric aging and alteration are later inserted into both the upper and lower mantle during subduction. Some portion of the elements added to the crust on-axis (e.g., Li, B, Rb, Cs, Sr, U, Mg) are later extracted in subduction zones by melting or dewatering of the down-going slab. The rest is incorporated into the mantle for long-term storage and may return to Earth's surface at hot spots. Thus, to understand the crust-mantle circulation system, we need to more accurately determine the composition of the material that is subducted, and understand the processes occurring at the trench and beneath the island arc that modify subducted material. We also need to better understand the physical dimensions of mantle heterogeneity, how long heterogeneities exist in the mantle despite convection, and how the evidence for that mantle heterogeneity, through hot spots and other upwellings, reaches the surface.

Subduction zone cycling. The composition and volume of material being subducted at a trench strongly affects the dynamics of the forearc, and the eruptive products and explosivity of the volcanic arc. We are currently in an early stage of understanding the forcing functions that trace and balance mass, volatiles and energy through this primary Earth system. Cycling of mass, volatiles and energy through the shallower part of this system can be evaluated by (1) drilling in the forearc and lower-plate crust, (2) monitoring of hydrothermal vents and diapiric upwelling zones in forearcs, (3) sampling of arc volcanoes and backarc volcanism, and (4) determining the composition, physical properties and PT history of arc lower crust and upper mantle via study of tectonically exhumed arc sections, investigations of mantle fragments in active arcs, and seismic investigation of active arcs. Both passive and active seismic experiments are critical for imaging the structure and velocity distribution through an active subduction system, but very few "modern" experiments have been undertaken. Geochemical tools are well-developed for studying the volcanic output in arcs (see Subduction Recycling box on page 128). These can be used to evaluate the variation of input fluxes for the global arc system, after "calibration" of the geochemical signals with respect to quantified input fluxes in at least one location.

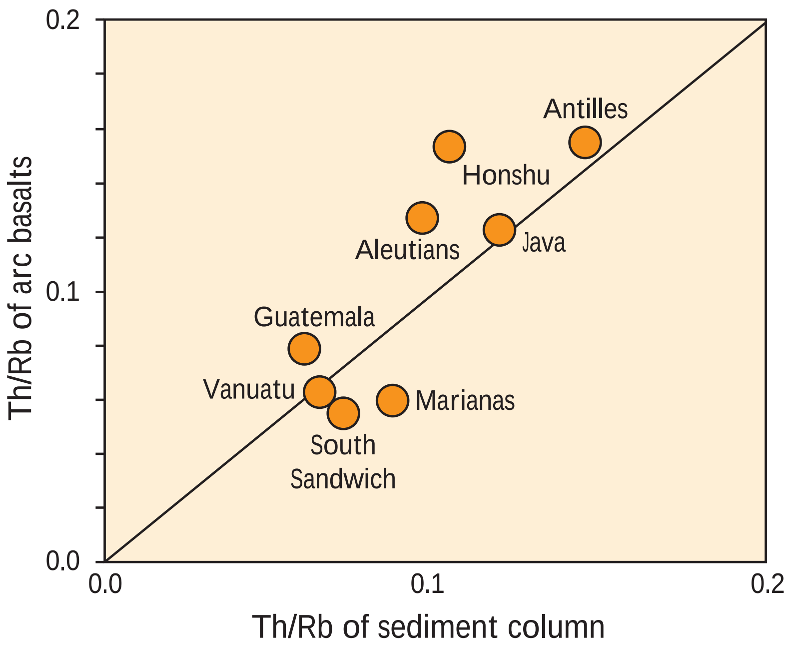
Subduction Recycling

Contributed by Terry Plank, Boston University

Seismologists discovered subduction zones in the 1960s and identified them with sinking seafloor at the edges of the ocean basins. With this discovery, a critical piece of plate tectonic theory rapidly fell into place. It took much longer, however, for scientists to understand why subduction generally leads to arc volcanism on the overriding plate. Subduction zones are cold and mark regions of dominant crust and mantle downwelling, neither of which are favorable conditions for melting. The presence of gas-charged eruptions, however, led to the theory of water recycling and mantle melting at subduction zones: seawater trapped in minerals in the subducting plate eventually escapes during subduction, promotes melting in the overlying mantle, and charges volcanic eruptions. The full implications of this water cycle are profound—it keeps water at the surface of the Earth, leads to juvenile magma additions that form the continental crust, and transports material from the subducting plate to the volcanic arc in a large recycling process.

The last ten years have seen a remarkable variety of evidence to support recycling of material through subduction zones. Virtually all of this evidence is based on chemical tracers, as geophysical techniques lack the resolution to image both the downward and upward flow of crustal material through the subduction zone, to 100s of km depth. The detection of the cosmogenic tracer ^{10}Be in arc magmas requires rapid recycling (a few million years) of young material through the subduction zone. Direct measurements of magmatic H_2O contents, which are made difficult due to the degassing that inevitably accompanies eruption, verified the water cycling and wet-mantle melting theories. The discovery of high pressure blueschist minerals actively venting from serpentine mud volcanoes in forearcs also provided material evidence of upward recycling. Finally, with the abundance of deep sea drill holes seaward of trenches, and rapid geochemical analytical techniques to characterize the subducting material, we are beginning to discover a multitude of chemical tracers that bear witness to material cycling. For example, the Th/Rb ratio in arc volcanics directly inherits the Th/Rb ratio in the local subducting sediments (see figure). Other tracers, such as B and Pb isotopes, are sensitive to material recycled from the basaltic layer of the downgoing plate.

While subduction recycling is now being resolved to ever fine temporal and spatial scales, future efforts will focus on how and how much recycling occurs. Subduction was invented as a tectonic phenomenon, where plates are destroyed as they sink into the mantle. We now recognize that subduction zones act as a kind of factory, processing raw materials at the trench into new continental crust, with volcanic emissions to the atmosphere, and waste products that continue into the mantle. The processes that happen inside the subduction factory are thus critical to the rates at which the continents grow and how the solid Earth and atmosphere evolve chemically. Do sediments melt in the subduction zone, or merely dehydrate and decarbonate? What reactions in the slab control the location of earthquakes, the loss of water, and the proportion of material lost from the subduction zone? How deep does the mantle melt beneath arc volcanoes, and is melting solely driven by water fluxes or by decompression as well? These metamorphic, melting, advective and tectonic processes will only be understood through multidisciplinary programs that bring together theoretical and experimental seismologists, geochemists and geodynamicists.



One-to-one correlation between Th/Rb in arc basalts and Th/Rb in local bulk sedimentary column subducted at the trench. This relationship provides strong support for the cycling of marine sediment components through the subduction zone, and back out the volcano. Only margins with a high Rb sediment flux are plotted (> 3 g/yr/cm arc length), as low sediment flux margins are dominated by oceanic crust and mantle contributions. From M. Johnson and T. Plank, *Geochem., Geophys., Geosystems*, **1**, 1999.

Determining the mass balance through a subduction system will allow us to evaluate what processes have been important in forming continental crust; whether continental crustal mass increases, decreases or stays the same; and whether convergence will lead to tectonism and mountain-building at a particular location. The geochemical and geophysical tools for addressing these problems exist, and we expect substantial progress to be made in the next decade.

Hot spots as samples of plume circulation. Hot spot volcanism provides samples from the deep Earth that are the most direct evidence that the mantle is chemically, isotopically and thermally heterogeneous. This heterogeneity is maintained, despite convective mixing of the mantle, possibly via input of subducted materials on a short time scale. Many investigators feel that hot spots are the surface manifestation of buoyant plumes rising from the lower mantle. If so, they are a fundamental part of Earth's basic heat engine. Compared to the present day, this process may have been even more significant at certain times in the past. For example, during the Cretaceous, massive plume-type volcanism led to the eruption of many large igneous provinces (or LIPS), as indicated by formation of major oceanic plateaus of similar age.

With an improved understanding of how hot spots sample the mantle, we can obtain a chemical map to complement the increasingly sophisticated models we are now producing of the physical flow system. In the foreseeable future, a combination of increasingly high-resolution seismic images and plate-kinematic reconstructions of the positions of ancient subducted slabs will permit the recovery of major features of the mantle flow system on time scales of 10^8 years. When combined with chemical information from hot spot lavas of various ages, we will have powerful constraints for understanding the physical and chemical dynamics of the deep interior.

Many basic questions must first be answered concerning plumes and LIPs if we are to better understand the thermal structure and upwelling dynamics of mantle plumes. How large are plumes? What are the relative roles of thermal and chemical heterogeneities in plume buoyancy? From what depth do they originate? What flow do they entrain? What is the rate of upwelling in plumes, and how much is their ascent perturbed by flow in the surrounding mantle? If plumes come from the lower mantle, how do the phase transitions at approximately 670 and 410 km depth affect their diameter and upwelling velocity? How do plumes interact with both the continental and oceanic lithosphere? What causes the large differences in flux between plume-type volcanism in LIPs and that in the less voluminous present-day, hot spot volcanism? It will be necessary to carry out careful seismic imaging experiments and modeling studies to ascertain this information. These must be combined with satellite gravity mapping, extensive sampling, thermal subsidence determinations, and deep drilling into some of the LIPs to understand their ultimate role in Earth's dynamics.

Melting and melt transport

Igneous activity is the dominant process of mass transfer between Earth's interior and the crust. More than 20 km^3 of igneous crust is formed annually along the vast mid-ocean ridge system, accounting for over 90% of the global volcanic activity. In the distant past, these rates may have been greater by more than a factor of four and, at times, vast outpourings of lava led to the formation of "large igneous provinces" (LIPs) in both oceanic and continental settings. LIP creation, along with increased rates of seafloor spreading, affected the volume of the ocean basins resulting in the long-term increase in sea level and the creation of vast shallow seas (Figure 21). The combined effects of LIP- and rapid oceanic crust formation appear to have had a long-term, direct effect on global climate warming and an indirect effect on the way that nutrients were cycled and carbon was sequestered as sea levels rose in the early Cretaceous. Not until the early part of the Cenozoic did increases in continental weathering rates (as indicated by the strontium isotope record in Figure 21) appear to draw down the high levels of CO_2 in the atmosphere of the Cretaceous and early Cenozoic.

Magmatic activity also brings heat and volatiles from the mantle and drives hydrothermal circulation in the oceanic crust, which in turn provides the energy and nutrients to support unique, chemosynthetically based biological communities on (or below) the seafloor (see The Ocean Below the Seafloor chapter and Figure 11 on page 76). Subduction of oceanic lithosphere into the mantle at convergent margins is associated with additional igneous activity, forming the arc volcanoes that rim the Pacific and which are the most explosive and dangerous form of volcanic activity on the planet. Arc magmatism is also a primary means of continental crust formation.

One of the most important and poorly understood aspects of volcanism is the remarkable upward focusing of magmatic activity from broad melting regions in the mantle, several hundred km in lateral dimensions, into discrete eruptive centers. This focusing is crucial because it concentrates mass and energy transfer from the mantle to the crust, greatly magnifying thermal and chemical gradients which drive hydrothermal and biological processes. Thus, beneath mid-ocean ridges, melt forms in a region ~ 200 km wide, but rises to form igneous oceanic crust and seafloor volcanism in a region less than 10 km wide. At fast-spreading ridges, this volcanic structure is "two-dimensional," as it is essentially continuous for 1000s of km parallel to the ridge axis. In addition, especially at slow-spreading ridges, delivery of melt is focused in three dimensions, with most melt delivered from the mantle to the base of the crust at the centers of "magmatic segments" spaced at ~ 50 km intervals along the ridge axis. Three-dimensional focusing of melt transport from the mantle to Earth's surface is also observed in island arcs, where linear arrays of contemporaneous, discrete volcanic centers are formed; in large igneous provinces, with eruptions from both fissures and discrete volcanoes, probably underlain by radial dike swarms emanating from a mantle plume axis; and in hot spot chains, where sequential, discrete volcanic islands are formed.

The dynamics of both solid convection and melt flow networks may be central to understanding how melt is focused beneath these different volcanic systems, and what factors control the variation in behavior from hot spot to arc to spreading ridge. What leads to focused magmatic centers, and what are the patterns of solid mantle flow in different geodynamic settings? What mechanisms of melt transport (diffuse porous flow, focused porous flow, or transport in fractures) dominate in different settings? How do these factors affect the

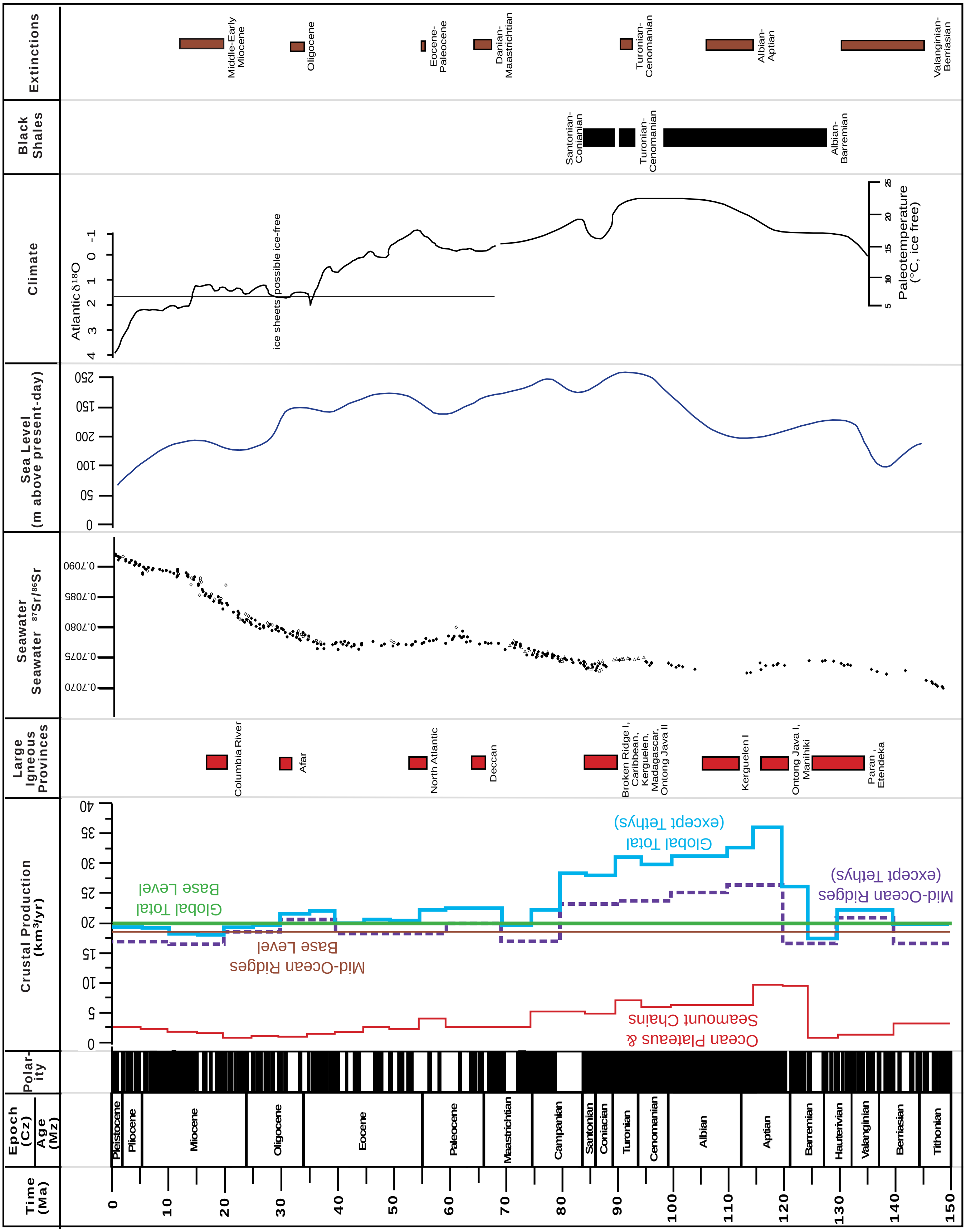


Figure 21. Temporal correlations among geomagnetic polarity, crustal production ages, LIPs, seawater strontium isotope ratio, sea level, climate, black shales and mass extinctions (Figure compiled by Millard F. Coffin, The University of Texas at Austin).

composition and spatial organization of magmatic products? How does magmatism affect the geotherm, and vice versa? These questions lie at the heart of our understanding of how the oceanic crust, arc volcanoes, and hot spot islands are formed.

Because of their relative simplicity, and the unique window they provide into the composition and thermal structure of the upper mantle, mid-ocean ridges will continue to be the focus of many petrologic and geophysical studies of oceanic igneous processes. There is general agreement on a basic theory in which melting beneath ridges is driven by adiabatic decompression (upwelling) of mantle material, in response to plate spreading. Within this conceptual framework, investigators are now focusing on magmatism in other (more complex) oceanic settings, including convergent margins, oceanic hot spots, oceanic plateaus and rifted margins to address more difficult questions regarding melt extraction mechanisms, source heterogeneity, and the mechanisms of accretion of igneous crust (Figure 22).

With recent advances in geophysical imaging techniques, mantle geochemistry, and the computational capability to characterize the structure of complex natural phenomena and to model three-dimensional geodynamic systems, the topic of melting and melt transport is poised for major breakthroughs in the coming decade. Arrays of ocean bottom seismometers with broadband sensors and the capability of deployments of a year or longer will allow experiments to be carried out to illuminate the nature of diapiric mantle upwelling and the spatial organization of melt conduits beneath ridges, plumes and arcs. Coincident with these seismic arrays, magnetotelluric stations, measuring the electrical conductivity of the mantle to depths up to 200 km, can provide critical additional constraints on melt connectivity and the influence on mantle rheology. A few such experiments, such as the MELT experiment at the East Pacific Rise spreading ridge (see Imaging Mantle Flow box on page 134) and the ICEMELT experiment where a hot spot and the Mid-Atlantic Ridge are juxtaposed in Iceland, have recently been completed with great success. They provide an excellent template which can easily be exported to different geodynamic settings. New geochemical tools, such as uranium decay series disequilibria studies, will be used to place important constraints on the melting process. Additional work, from field mapping, drilling and laboratory experiments, will be required to determine whether melt migration and focusing can be explained by flow in microscopic pores along crystal grain boundaries, or whether large, more focused melt pathways are required. By integrating geophysical, geochemical and rheological constraints, a predictive model of melting and melt migration is within reach in the coming decade. This predictive model can be used to understand the factors controlling mantle flow and the geotherm in different tectonic environments and those leading to melt focusing, and to gain insight into the more general problem of spontaneous spatial organization in all natural fluid flow systems.

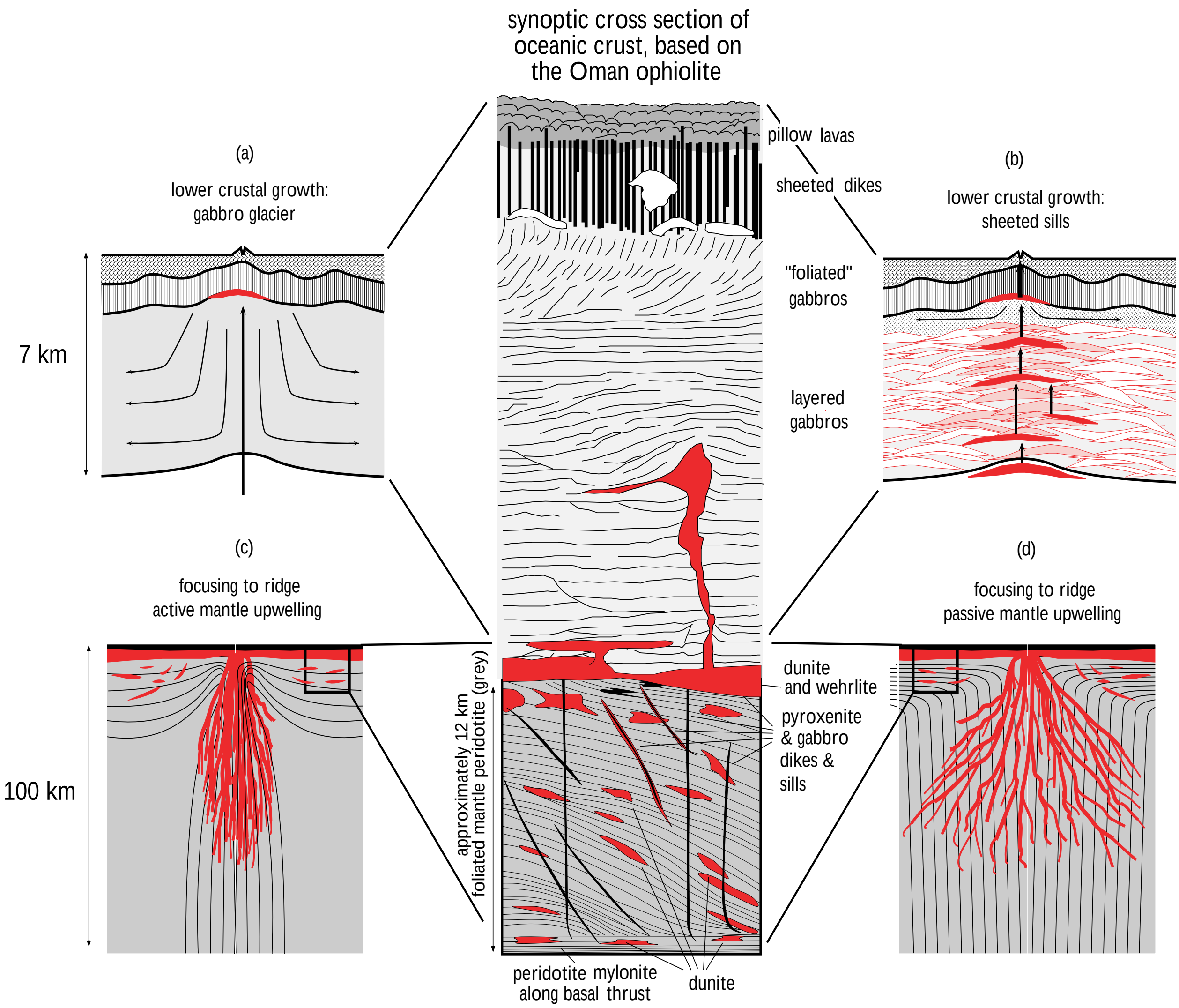


Figure 22. Schematic illustrations of proposed, end-member models for igneous accretion of the lower crust at fast-spreading mid-ocean ridges and for focusing of melt extraction in the mantle from a ~100 km wide melting region to a ~ 10 km wide crustal accretion zone beneath the ridge axis. (a) "Gabbro glacier" model. Ductile flow downward and outward from a single, shallow axial magma chamber forms the entire lower crust. (b) "Sheeted sill" model. Melt transport by hydrofracture and in situ emplacement of the lower crust by sill intrusions. Most gabbros are crystallized at their current depth of emplacement. (c) Focused solid mantle upwelling, due to buoyancy driven mantle convection, with mainly vertical melt transport. (d) Passive solid mantle upwelling, due to plate spreading, with coalescing melt flow conduits. Central panel is a summary cross-section of the Oman ophiolite, where upper mantle and lower crustal exposures allow testing of these hypotheses. Reprinted with permission from *Nature* (Keleman, P.B., N. Shimizu, and V.J.M. Salters, *Nature*, **375**, 747-753, 1995), copyright 1995 Macmillan Magazines Ltd.

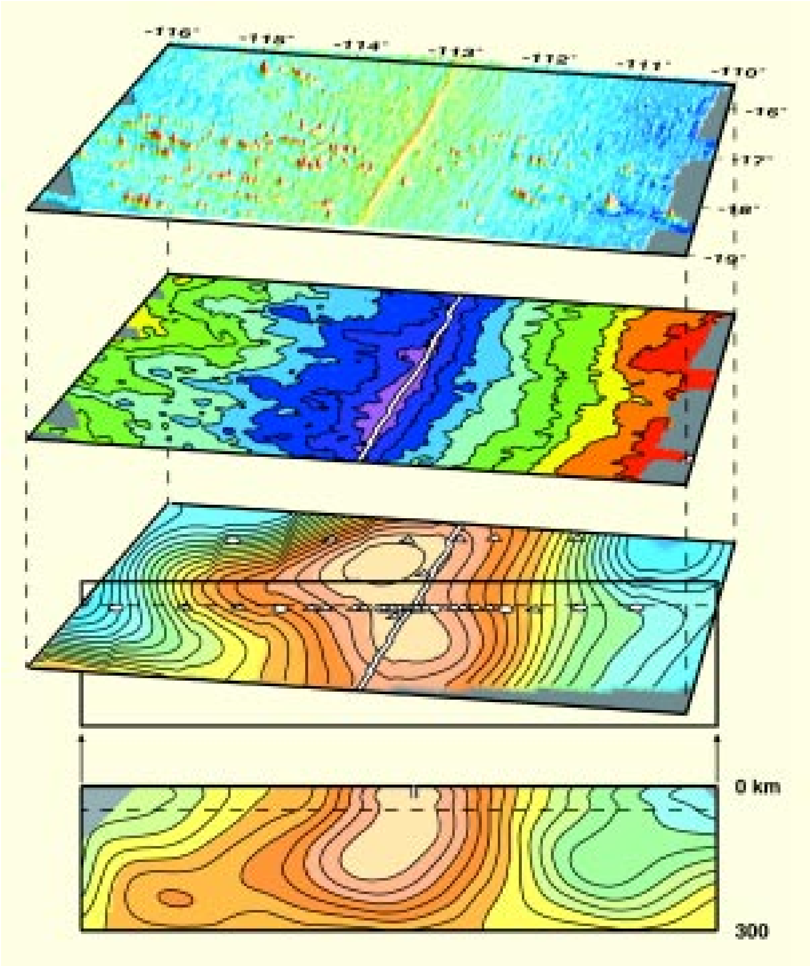
Imaging Mantle Flow and Melt Generation

Contributed by Douglas Toomey, University of Oregon

Observations of oceanic ridges from the Mantle Electromagnetic and Tomography (MELT) experiment are yielding new insights into mantle flow and magma generation. Prior to the MELT experiment, available data imposed only limited constraints on the nature of upwelling and melting beneath spreading centers. The location of eruptions and intrusions, the thickness of crust formed from the magma, the composition of mid-ocean ridge basalts, and low-resolution gravity and teleseismic data formed the basis of prior knowledge about the geometry of melt generation region beneath mid-ocean ridges. To provide more detailed constraints, MELT employed a combination of measurement methods, including body wave tomography, surface wave dispersion studies, and magnetotelluric profiling. These studies of seismic and electromagnetic wave propagation constrain horizontal and vertical variations in seismic velocity and electrical conductivity in the mantle that are associated with the presence of melt or with the upwelling that generates the melt.

The southern East Pacific Rise (SEPR) between 0° and 30°S accounts for more than 20% of Earth's annual budget of plate creation, an amount exceeding that of the Mid-Atlantic and Southwest Indian Ridges combined. It was within this region of pronounced upwelling, near 17°S, that the MELT experiment was conducted. In combination with earlier studies, the experiment revealed asymmetries in structure that extend from the seafloor through at least the upper 100 km of the mantle. The region west of the rise, relative to the east, is characterized by faster absolute plate motion, slower seafloor subsidence, more abundant seamounts, less dense mantle, greater shear wave splitting, lower seismic velocities and higher electrical conductivity. Seismic and electromagnetic measurements demonstrated that the distribution of melt in the mantle is asymmetric; at depths of several tens of kilometers, it is more abundant beneath the Pacific plate to the west of the axis than beneath the Nazca plate to the east.

MELT investigators attributed the asymmetry in melt and geophysical properties to three possible factors: asymmetric flow passively driven by coupling to the faster moving Pacific plate; an off-axis center of dynamic upwelling; or anomalous melting of an embedded compositional heterogeneity. Ongoing studies indicate that westward migration of the SEPR alone, cannot cause the asymmetries documented for this area. Asthenospheric flow from hot spots in the Pacific superswell region back to the migrating ridge axis in conjunction with the asymmetric plate motion can create the observed anomalies. These results support the hypothesis that hot spots feed the oceanic asthenosphere that subsequently provides the return flow to the ridge axis. The asthenospheric flow probably involves anomalously hot mantle that actively flows away from the hot spot, but either anomalous temperatures or pressure-driven flow are sufficient to cause asymmetries in melt production that may be responsible for the asymmetries in seismic velocities, seamount abundance, seafloor subsidence and electrical conductivity.



Seafloor topography, gravity anomalies, seismic Rayleigh wave velocities and anomalous shear wave velocities measured in the Mantle ELectromagnetic and Tomography (MELT) Experiment on the East Pacific Rise (the center of the image is located at 17°S, 113°W; image width left to right is 640 kilometers; bottom image is a vertical cross-section extending from the seafloor to 300 km in depth). Ocean-bottom seismometers were used to detect partial melting of the mantle and upwelling of magma, which erupts at mid-ocean ridges. Image courtesy of D. Scheirer, based on data from D. Scheirer, D. Forsyth and D. Toomey.

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The composition of the lower oceanic crust and nature of the oceanic Moho

Oceanic crust covers over 50% of Earth's surface, yet the composition of the lower oceanic crust and the nature of the oceanic Moho remain largely unknown. The deepest, continuous drill hole into the oceanic crust extends only slightly more than 2000 m below the seafloor, less than one third of the way through a typical geophysically defined oceanic crustal section. The 1971 ophiolite model defined at the Penrose Conference for oceanic crust associated the lower oceanic crust with a thick plutonic sequence of gabbros and the oceanic Moho with a transition from these igneous rocks to mantle peridotite. The identification of the Moho with the base of the gabbro section is the linchpin on which estimates of the volume of past and present basaltic volcanism in the oceans is based, and on which most current models of ocean crustal formation are built.

While the ophiolite model for the oceanic crust has been widely accepted and applied for nearly 30 years, it has never been directly tested with *in situ* sampling of the lower oceanic crust. Our knowledge of the geological structure, physical properties and alteration history of about two-thirds of the oceanic crust has been only inferred. Data include geophysical measurements, sampling of infrequent and incomplete exposures of deeper crustal rocks, usually in or near oceanic fracture zones, and sampling and measuring ophiolites, sections of presumed oceanic crust that have been tectonically exposed on land. Recent geological mapping and sampling along mid-ocean ridges have revealed striking differences in structure between fast and slow spreading ridges which were not foreseen based on observations of ophiolites.

These observations have revived speculation that serpentinite may be a significant component of the lower oceanic crust as originally proposed by Harry Hess in 1962. Hess believed that the relatively uniform depth of the Moho in the ocean basins did not reflect the thickness of the igneous crust but instead represented an alteration boundary in the shallow mantle between serpentinized and unserpentinized peridotite. If the Moho is an alteration boundary in some locations (e.g., along slow spreading ridges) but an igneous boundary at others (e.g., fast spreading ridges) how can this be reconciled with the composition of magmas erupting at oceanic spreading ridges, which show remarkably little chemical variation with spreading rate? Geophysical observations also reveal many features (i.e., depth to Moho, seismic velocity of the lower crust) which are largely independent of spreading rate. This paradox, and the validity of the ophiolite model, will only be resolved by direct, *in situ* sampling of the lower oceanic crust and Moho with drilling. Neither offset-section drilling, as currently carried out by the Ocean Drilling Program, nor studies of ophiolites, can provide the intact and tectonically undisrupted sections, or the integrated history of fluid flux and alteration, necessary to address this question.

Uncertainty over the composition of the lower oceanic crust and Moho, which has now existed for more than 30 years, has proven to be a major obstacle to advancing our understanding of a variety of problems. For example, the recovery of a complete oceanic crustal section is essential if we are to:

- determine the structure, composition, mineralogy and *in situ* physical properties of the oceanic crust and the geological nature of the seismic Moho;
- constrain estimates of present and past magma production from the oceanic mantle;
- develop models of oceanic crustal formation, especially of the lower oceanic crust;
- determine the deformation history of the crust;

- establish a standard lithologic section for correlation with major seismic discontinuities in the oceanic crust and upper mantle;
- measure the bulk composition and alteration history of the oceanic crust in order assess the geochemical mass balances at ridges and subduction zones;
- constrain the extent to which seawater-oceanic crust chemical exchanges are microbially mediated
- determine the source of marine magnetic anomalies;
- determine the net and long-term buffering capacity of the oceanic crust in controlling the composition of seawater.

Drilling a complete oceanic crustal section has been a goal of marine geologists since the days of the MOHOLE Project in the 1950s, and has been repeatedly articulated in scientific planning documents ever since. For nearly half a century the technology to achieve this goal has not existed and ocean drilling has been limited to only the uppermost few km of the oceanic crust. However, with the oil industry now rapidly moving beyond the edge of the continental shelf and drilling in deeper and deeper water, this situation is rapidly changing. Several riser-equipped drillships capable of operating in water depths of >2000 m are now operational and Chevron has just completed a well in 2352 m of water in the Gulf of Mexico. This technological breakthrough has finally brought the goal of sampling the lower oceanic crust and Moho within reach.

Mechanisms and controls on lithospheric deformation and faulting

Tectonic stresses deform the crust and upper mantle. When these stresses exceed the strength of rock, faulting occurs. The resulting earthquakes, especially those that occur in subduction zone settings or along transform faults, can be large and destructive. Plate tectonics provides a quantitative framework within which lithospheric deformation and faulting can be understood, and a first-order explanation for the global distribution of both seismicity and earthquake mechanisms. Increasingly, investigations are focusing on the deformation process itself, and the still poorly understood interplay among tectonic stress, rock rheology, fluid distribution and faulting. Critical questions include: How do large faults slip at unexpectedly low stress levels? Why do some faults lock, eventually leading to large earthquakes, while others slip nearly aseismically? What is the origin of low-angle detachment faults? How is regional stress localized and magnified so as to initiate faults?

Studies in the oceans, and along their margins, will play a critical role in addressing these fundamental questions in the coming decade. Some types of faults are restricted to oceanic settings. For example, megathrusts associated with subducting plates occur almost exclusively in a submarine setting. In addition, because of the simpler rheology and geological history of oceanic lithosphere compared to that of continents, the oceans provide a unique natural laboratory within which to study all kinds of deformation processes. With the rapidly advancing technology for carrying out detailed geological and geophysical studies on the seafloor, and for long-term, *in situ* monitoring of fluid pressures, fluxes and chemistry, temperature, seismicity and strain, there are exciting opportunities for advances in several important areas.

Seismogenesis in subduction zone megathrusts. Subduction zone megathrusts (Figure 23) produce the largest and potentially most destructive earthquakes and tsunamis. Despite the societal importance of these great earthquakes, little is known about the seismogenic zone that produces them. What factors are

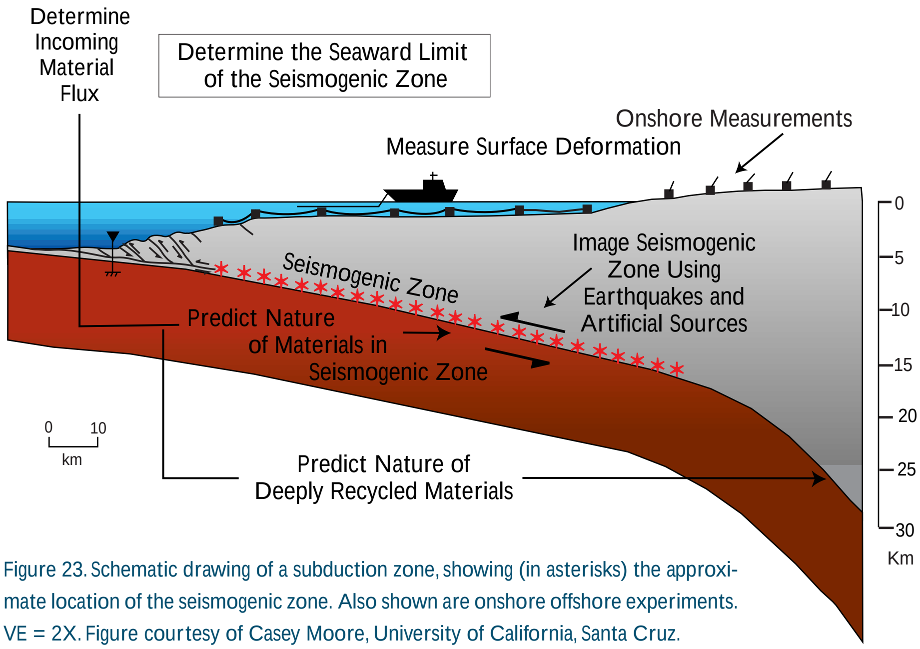


Figure 23. Schematic drawing of a subduction zone, showing (in asterisks) the approximate location of the seismogenic zone. Also shown are onshore offshore experiments. VE = 2X. Figure courtesy of Casey Moore, University of California, Santa Cruz.

responsible for generating earthquakes in one area and not in others? What processes control how frequently large earthquakes occur? What properties of an active fault system might be measured to better assess seismic risk?

The Coulomb failure model has provided a successful conceptual framework for studies of accretionary subduction zones. This model predicts the response of the sedimentary wedge to changing geometry, and explains so-called out-of-sequence faults at the back part of a growing wedge. However, this model does not explain the origin of the low-angle thrust fault, or detachment zone, which forms the base of the wedge. This fault develops along flat-lying sedimentary layers and appears to slip at unexpectedly low stress levels. This has been called the "low stress paradox," and it is not unique to subduction zones. Instead, it is a fundamental problem in understanding lithospheric deformation in a variety of tectonic settings, including major continental strike-slip faults like the San Andreas system. Evidence suggests that many of these major crustal faults fail at resolved shear stresses an order of magnitude lower than would be predicted from laboratory measurements of the strength of crustal rocks.Various explanations have been proposed to account for these "weak faults" including the presence of low-strength material in the fault zone or the existence of high fluid pressures. Some have questioned whether such a paradox really exists. The resolution of this problem is a necessary prerequisite for developing a physical theory relating far-field tectonic stresses to the local stress field, and the nucleation and propagation of seismic rupture.

An ideal natural laboratory to study the faulting process is found along subduction zones where the oceanic crust descends into the mantle. This zone lies within a forearc where sediments undergo compaction, lithification and dehydration as they underthrust at a low angle. The low angle of thrusting means that factors that control the partitioning of strain, the flow of water and other volatiles, the formation and behavior of faults, and the onset of earthquake-generating slip, are all relatively accessible (often at depths of less than 8-10 km), as compared to other types of major crustal faults.

To understand the dynamics of subduction zone earthquakes it is necessary to go to *a currently active seismogenic system to*:

- relate patterns of seismicity with seismic images of the main zone of thrusting, using such tools as regional ocean bottom seismograph networks, two-dimensional and three-dimensional seismic data and, ultimately, drilling;
- establish which parts of the thrust are locked and which are slipping, utilizing onshore and offshore geodesy, detailed seismic arrays, strain meters and drilling;
- determine the fluxes of solids and fluids through the subduction zone with drilling, surface experiments, geochemistry, and seismic and electromagnetic imaging of the subduction system;
- monitor change in seismicity, strain and fluid flux in the seismogenic zone;
- determine the nature and behavior of the materials in the seismogenic zone.

This kind of comprehensive study of a subduction zone megathrust, in concert with laboratory experiments and theoretical modeling, will help define the processes that control earthquake cycles, and improve estimates of seismic risk for major population centers located near oceanic subduction zones.

Mechanics of extensional faulting in oceanic lithosphere and at passive continental margins. A growing body of observational evidence has shown that when continents rift, deformation is concentrated on a few extremely large faults that apparently accommodate displacements of up to several hundred kilometers. The continental lithosphere in some places has been stretched to four times its initial extent, often on what appear to be large, low-angle listric-type (shallowing with depth) normal faults similar to those which have been mapped in areas like the Basin and Range Province in the western United States.

The existence of large, low-angle normal faults which accommodate large amounts of slip has been controversial for many years. Although the geological evidence for these faults in various regions of active extension is compelling, their existence cannot be explained by classic studies of fault mechanics. If the maximum principal stress in these extensional settings is approximately vertical, slip on planes shallower than 30° would conflict with the Coulomb failure criterion. This low-angle slip theory is supported by seismic observations in regions of active continental extension, such as the Aegean, where seismicity indicates that strain is being accommodated on high-angle, planar normal faults. This has lead to speculation that these faults initiate as steep planar faults which rotate to a shallower dip as displacement increases, or that they "roll-over" at the surface so that they dip gently near the surface but dip more steeply at depth. An even more puzzling problem is why these faults form at all. The integrated strength of the lithosphere, which is relatively well known from observations of plate flexure and laboratory measurements of rock mechanics, is five to ten times greater than even the largest estimates of the forces available to drive plate motions. Thus, in order to form these faults, and to accommodate a large component of plate motion for up to a few million years, a mechanism must be found to either concentrate and magnify these tectonics stresses, or to locally reduce the strength of the lithosphere.

The answers to these long-standing and fundamental questions of fault mechanics and crustal deformation will probably be found in the oceans. Here it is possible to study faulting occurring within an active extensional setting, with a much simpler crustal and lithospheric rheology, and geological history, than in most continental regions. The recent discovery of what may be low-angle detachment faults along some slow-

Megamullions in Oceanic Crust

Contributed by Brian E. Tucholke, Woods Hole Oceanographic Institution

Large features along the slow-spreading Mid-Atlantic Ridge and Southwest Indian Ridge have along- and across-axis dimensions of 15 to 40 km, exhibit distinctive domed or turtleback shapes, and contain conspicuous grooves or corrugations in their surfaces that parallel the direction of seafloor spreading (Figure A). Gravity studies and limited rock samples also indicate that these "megamullions" expose deep sections of the lower ocean crust and upper mantle.

Megamullions have been interpreted as crustal blocks exhumed by long-lived and areally extensive normal faults (detachment faults) at the ridge axis, with the corrugations formed by irregularities in the fault trace (Figure B). Breakaway and termination ages established from seafloor magnetic isochrons indicate that the detachment faults accommodate slip for periods of at least 1.0 to 2.6 million years. These are extremely long periods compared to slip durations on most normal faults in ocean crust, and they suggest that the faults are unusually weak.

If megamullions are created by detachment faulting, they may expose cross sections of relatively normal ocean crust and uppermost mantle. Mapping, rock sampling and drilling of these features has the potential to provide major new insights into the processes, cyclicity and time scales of tectonism, magmatism, and fluid flow in deep, normally inaccessible sections of the crust and mantle. Furthermore, megamullions have characteristics very similar to those of metamorphic core complexes in continental extensional environments such as the Basin and Range in the western United States, where rocks have been exhumed from depths up to ~15 km. Comparing and contrasting data from the continental and oceanic realms will lead to a much more comprehensive understanding of extensional tectonism, magmatism, and deep structure of Earth's lithosphere.

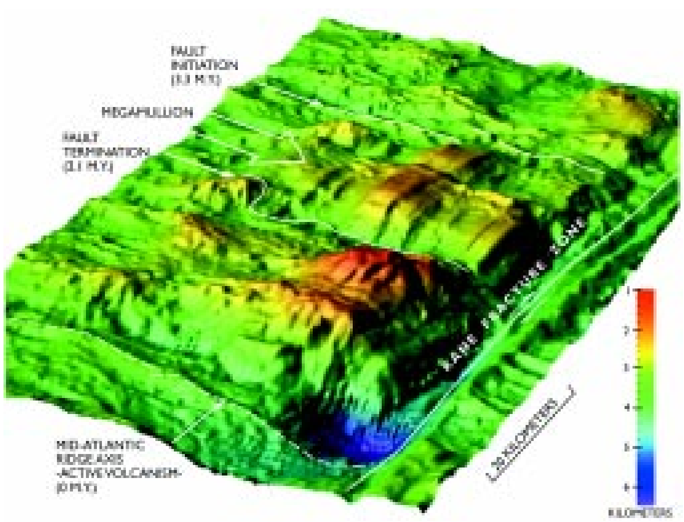


Figure A. Computer-generated perspective view, looking to the southwest, of a megamullion that developed south of Kane Fracture Zone on the Mid-Atlantic Ridge between about 3.3 and 2.1 m.y. ago. The megamullion is interpreted to be exhumed by a long-lived detachment fault. Its surface is corrugated by prominent ridges and grooves that extend ~east-west in the direction of seafloor spreading. High-angle scarps, probably formed as the feature was exhumed and rotated, locally cut the megamullion surface perpendicular to the corrugations (see the interpretive cross sections in Figure B). The image is based on multibeam sonar surveys that give complete bathymetric coverage in the view area.

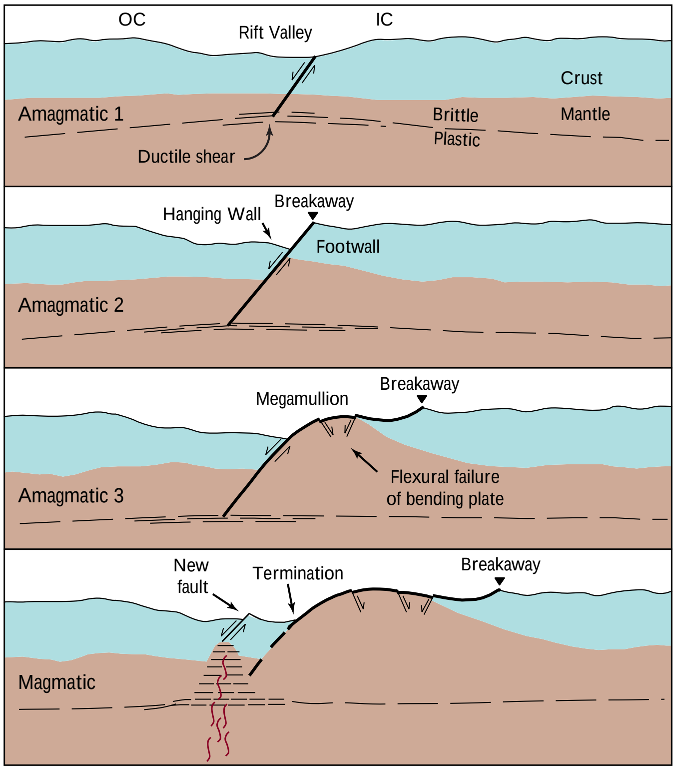


Figure B. Schematic, sequential cross sections that interpret a megamullion as crust and upper mantle exhumed by a long-lived detachment fault (bold line) during a period of seafloor spreading when magmatism is limited or absent. The plane of the sections parallels the directions of seafloor spreading and the corrugations on the megamullion surface. The detachment fault ceases to slip and megamullion development terminates when a new fault breaks through rift-axis crust that is weakened by renewed magmatism (adapted from Tucholke, B.E., J. Lin and M. Kleinrock, *Jour. Geophys. Res.*, **103**, 9857-9866, 1998).

spreading mid-ocean ridges provide a particularly exciting opportunity to address these problems (see Megamullions box on page 139). It should be possible to find examples of currently active detachment fault systems along a slow spreading mid-ocean ridge. In this very young, unsedimented crust the upper and lower crustal blocks and the intervening detachment surface can be readily mapped and sampled by submersible or dredging. Seismic and seafloor geodetic instrumentation can monitor motion along the fault and determine if slip is occurring on very low angle faults. Finally, drilling can sample the active fault zone and determine if processes such as serpentinization are responsible for the localization of strain along the detachment surface. The insight provided by a comprehensive study of this kind could lead to a new theory of faulting and a resolution of the lithospheric strength paradox that applies to both continental and oceanic crustal tectonics.

Transform faulting. The relatively simple tectonic setting of oceanic transform faults make them an attractive target for studies of earthquake fault mechanics. Oceanic transform faults show the peculiar behavior that although low resolved shear stresses are found on active transform faults, high shear strength (10 to 100 times the stress drops of typical transform earthquakes) characterize fracture zones beyond the transforms. This high shear strength is capable of supporting scarps 1 km or higher along fracture zones. This system represents an extreme example of the generalization that low recurrence rates often show the greatest stress drops, in an environment where apparently nothing changes except the slip rate.

Another unusual feature of oceanic transforms is the occurrence of "slow" earthquakes. These events are characterized by slow, low-frequency deformation prior to the initiation of high-frequency deformation. The two components of rupture can occur on spatially associated but distinct faults. These slow earthquakes appear to occur most frequently along transform faults and this peculiar rupture mechanism may be related to the presence of serpentine in the upper mantle.

Transform-fault studies will require seismic arrays, careful imaging, seafloor geodesy, geochemical sampling and drilling, as well as carefully placed long-term observatories.

Time scales of magmatic and tectonic processes

During the past four decades the ocean basins have been mapped and sampled with an increasingly sophisticated array of tools. These tools have enabled scientists to develop and refine the plate tectonic paradigm, as well as discover seafloor hydrothermal vents with their unique biological communities. They also have provided the data to accurately reconstruct the tectonic history of all of the major ocean basins over the past 200 million years. While we have made great strides in recent years in spatially characterizing the seafloor, and determining its evolution on geologic time scales, we are just beginning to study volcanic, tectonic and hydrothermal processes on the shorter, and more societally relevant, time scales, which characterize these processes. We now realize that in many cases comparatively rare, large events such as earthquakes, landslides or volcanic eruptions may dominate changes in the landscape. Without the ability to document and study these short-lived events we will never be able to fully understand how the oceanic crust is formed and evolves over time, or how the associated magmatic, tectonic, hydrothermal and biological processes are linked.

The questions involved are important and fundamental. What processes control the recurrence interval of large earthquakes on subduction zone thrusts or along major transform faults? What variations in *measurable* properties (e.g., fluid fluxes or chemistry, seismicity, strain accommodation) can be used to better assess potential seismic risk? Why is oceanic island volcanism episodic and what determines the temporal aspects of this volcanism? What is the episodicity of major spreading events along the mid-ocean ridge system? Is there a relationship between eruptive frequency and spreading rate (or magma supply)? Is crustal construction dominated by a few, infrequent and very large events or by much more frequent, smaller events? How are magmatism, tectonism and fluid flow linked in these active systems?

The investigation of these dynamic systems will require a new methodological approach, one which involves the acquisition of long-term observations or time-series, building on and complementing the surface-ship, expeditionary approach which has dominated the conduct of oceanography since the days of the HMS *Challenger* Expedition more than a century ago. This "observatory" mode of science will entail a shift away from more traditional short-term spatial mapping and sampling to more interdisciplinary investigations, using *in situ* sensors to make continuous measurements on or below the seafloor, and in some cases conducting perturbation experiments. Seafloor observatories (Figure 24) have been set up on a small scale, and for limited periods of time, but a much more extensive effort must be undertaken in the coming decade to address the numerous questions related to the temporal- and spatial-scales of processes such as diking, faulting, fluid flow and crustal deformation. Given the range of time and space scales involved, a variety of approaches will be required. "Active Processes" observatories must be located where Earth systems are currently most active near the surface, such as in subduction zones and related magmatic arcs, mid-ocean ridges and mid-plate volcanoes. Due to the unpredictability of volcanic and tectonic events, in many cases highly portable and rapidly deployable systems will be required. More permanent "Global Network" observatories will also be needed, both to provide geometrically uniform global coverage (e.g., broadband seismometers for imaging Earth's interior) and to provide a view of certain processes on a planetary scale (e.g., to measure global hydrothermal fluxes).

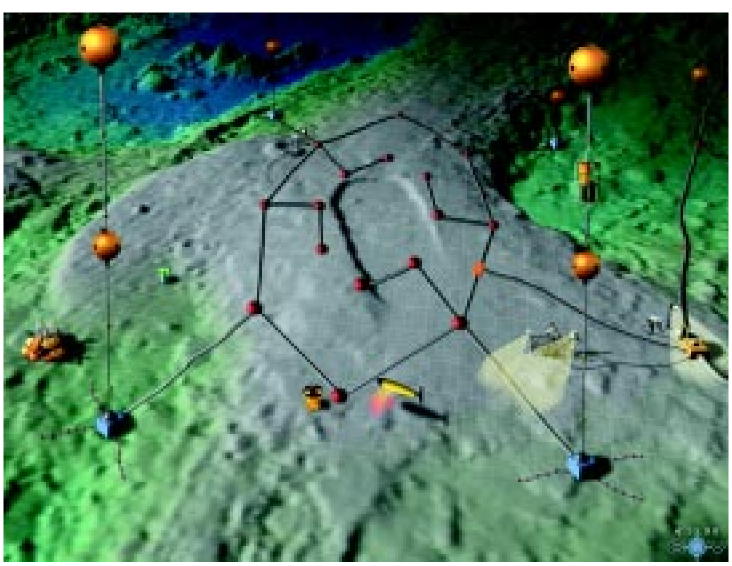


Figure 24. A conceptual design of a seafloor observatory to detect and characterize activity associated with an active seafloor volcano. Sensors include ocean bottom seismometers (red dots), moorings with current meters and nutrient monitors, AUV and benthic rovers to regularly resurvey the area, as well as cameras and lights. These sensors would be linked by cable to a junction box, where data would be transmitted back to shore in real-time either using a fiber optic cable or via satellite from a surface buoy. The cable or buoy would also supply power to these instruments and allow scientists onshore to remotely control the sensors providing a unique ability for sustained *in situ* observations in the submarine environment. Preliminary work on the establishment of an observatory such as this is being carried out by scientists from the NOAA Vents Program at Axial Seamount on the Juan de Fuca Ridge. Figure courtesy of John Delaney, University of Washington, Seattle.

WHAT MAKES PROGRESS POSSIBLE NOW?

Powerful new tools are now becoming available for studies in the oceans that offer unprecedented opportunities for future research into the dynamics of the solid Earth. These include:

- High-resolution seafloor imaging systems, and dating techniques for young volcanic rocks. This allows marine geologists to construct geological maps of the seafloor with a resolution comparable to those available to geologists on land.
- Increasingly sophisticated drilling technology, including the capability to drill while controlling borehole fluid pressure. This technology will allow the drilling of significantly deeper holes than has been possible to date, and permit drilling in previously inaccessible areas along our continental margins.
- Advances in analytical techniques, and the development of powerful new isotope and trace element geochemical methods, for studying the composition of the mantle and mantle melting processes.
- Explosion of GPS geodesy, and the ongoing development of seafloor geodetic techniques. This development allows the quantification of tectonic motions and crustal deformation with centimeter-scale resolution on the seafloor.
- Major advances in seismic imaging capabilities. These capabilities range from three-dimensional seismic reflection studies of sedimentary and crustal structure, to the development and availability in large numbers of ocean bottom seismometers for use in both active crustal studies and long-deployment teleseismic investigations.
- The complementary information on crust and mantle properties provided by electromagnetic techniques offers a new means of constraining dynamic processes. Magnetotelluric techniques can probe deep into the oceanic mantle and are sensitive to conductive phases such as partial melt and dissolved hydrogen. Controlled source techniques can measure the conductivity of the oceanic crust to look at issues as diverse as hydrothermal circulation and serpentinization of the lower crust in new ways.
- Technological advances in microprocessors, data storage capabilities, and telecommunications, making it feasible to establish permanent geophysical observatories on the seafloor with real-time data telemetry back to shore from anywhere in the world's oceans.

WHAT IS REQUIRED FOR PROGRESS?

A major challenge for the future is how to foster the development of new technology, and how to maintain this instrumentation, and the technical expertise to operate it, in the present funding climate. High-resolution multibeam bathymetry, side-scan imaging systems, and advanced seafloor sampling capabilities (submersibles, ROV, AUV, drilling) are essential for detailed seafloor geological studies. Multichannel seismics and large arrays of OBS/OBH are required for imaging crustal and upper mantle velocity structure in three-dimensions. Broadband seismic instruments will be needed for passive teleseismic imaging of deep Earth structure. Long-deployment OBS, repeat seismic surveys, and seafloor geodetic instruments (e.g., tiltmeters and strainmeters) will be required to monitor seismicity and crustal deformation in active tectonic areas. Heat flow measurements are needed to provide constraints on subseafloor fluid flow. This is particularly crucial near active volcanic zones. But, in these areas large local thermal gradients and the presence of cracked rock ensure that individual measurements are not representative. Methods must be found to collect more regionally representative data sets. Geochemical and petrological studies of volcanic and plutonic rocks, hydrothermal alteration, and venting of fluids on the sea floor are essential to understanding geochemical cycling in subduction systems and hot spots, determining the nature of the lower oceanic crust, and constraining the dynamics of melt transport and igneous crustal accretion. There is also a continuing need for well-constrained geodynamic models which carefully examine the range of possible behavior of simplified physical systems characterized by variation of a few, key variables. These models have been, and will continue to be, crucial tools in understanding available data and inspiring new observational programs. High P-T experimental work, especially on physical properties, with particular emphasis on the rheology of lower crust and upper mantle materials as a function of melt and/or volatile content, has proven to be a very valuable and growing field in the past five years, and we anticipate continued, rapid progress in this area.

Ocean drilling is an *essential* tool for future studies of the oceanic lithosphere and continental margins. Drilling provides samples of subsurface rocks and fluids, and the opportunity to measure *in situ* physical properties of the oceanic crust and lithosphere that cannot be obtained in any other way. "Conventional" ocean drilling from a *JOIDES Resolution*-type platform will remain crucial. This type of drilling is required for sampling the upper portion of the oceanic crust, especially on older seafloor where it is buried by sediment, for obtaining "time series" samples along ancient hot spot tracks, for sampling the submerged parts of arc volcanic lineaments, and for investigating the post-rift subsidence history of many continental margins. Deep drilling (depths of 6 to 8 km below the seafloor) with a well-control capability (e.g., a deep water riser system) is needed to attack many fundamental questions such as the composition of the lower oceanic crust and Moho, the nature of the seismogenic zone in subduction zones, and the nature of continental margins in areas that might contain hydrocarbons. The technological breakthrough to allow deep drilling provides a great new scientific opportunity. But, there are many challenges too, such as finding the best way to make this new capability available as a research tool, and supporting the much larger effort required for predrilling surveying, site characterization, and post-drilling investigations. The scale of effort required will be substantial and argues for a large, decade-long commitment and the involvement of the broader international community in a jointly managed and funded program along the lines of the current Ocean Drilling Program. We highlight this requirement because of the necessity for renewed international commitment to deep sea drilling early in the coming decade.

We need to establish seafloor observatories to make long-term observations, and to study short-lived volcanic and tectonic events. It is anticipated that a variety of approaches will be taken, from simple, relatively inexpensive autonomously recording observatories, to observatories with real-time data telemetry capabilities either via satellite from moored ocean buoys or using fiber optic cables from shore-based stations. This increasing emphasis on long-term studies, and investigating short-lived events, will require changes in the way in which marine research is conducted. NSF must develop sufficient budgetary flexibility to mobilize a response effort rapidly (within days or a few weeks at most) following a significant volcanic or tectonic event. NSF must also provide long-term funding for time-series measurements at observatory sites over periods longer than a typical two- or three-year grant.

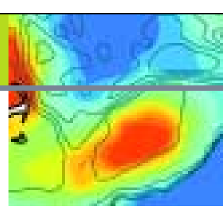
Increasingly, individual geologic provinces in the oceans (mid-ocean ridges, mid-plate volcanoes, subduction zones) are being viewed as part of a single, dynamic “solid Earth system.” Many processes (arc magmatism, seismogenic zone behavior, continental rifting and hot spot magmatism) cross the land-sea interface. Although most of the mid-ocean ridge system is under water, sometimes it is easiest to study where it lies above sea level in places like Iceland or in ophiolites. Similarly, drilling from island platforms may provide the most cost-effective way to address some questions about subduction zones or hot spot chains, despite the fact that these are largely submarine features. Imaging deep Earth structure will require seismic stations both on land and on the seafloor. The most efficient use of future resources will require close collaboration between land and marine geoscientists, and their funding sponsors.

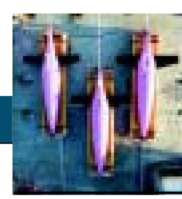
CONCLUSIONS

The oceans play a critical role in global systems that control Earth's environment. Physical, chemical and biological processes that take place in the oceans and modulate the environment are tightly linked. These processes control life in the seas, effect large transfers of energy, drive the pulse of climate change, impact the surrounding land masses, and respond to perturbations taking place outside the oceanic sphere. The importance of the oceans to society is rapidly growing, as is our need to understand the science of the physical, chemical, geological and biological processes operating in them. As the human impact on Earth's environment increases, the need to gain a fuller understanding of these oceanographic processes becomes all the more urgent. By building on the knowledge gained in the past few decades, and by making the necessary tools available to the research community, this scientific challenge can be met.

The individual oceanographic disciplinary reports have emphasized the large gains we have made over the past several decades in our appreciation of the complexity of oceanographic processes and point to the exciting opportunities made possible both by our increased understanding and by increases in technical capability. The findings and recommendations of this report support this view, but also emphasize the interdisciplinary nature of oceanographic studies. Future research in the oceans will require a more fully integrated approach, an increased emphasis on long-term monitoring and measuring, and further development of sophisticated numerical models.

The following paragraphs outline the major findings of this report and conclude with recommendations that are critical to advancing our understanding, and that will benefit society.





FINDINGS

An increased knowledge of the ocean fluxes that drive climate will be essential for evaluating climate change and for planning how to respond to, or ameliorate, this trend. Atmosphere-ocean exchanges of heat, fresh water, carbon, nutrients and other trace chemicals are not yet understood accurately enough for climate assessment and prediction. While all these fluxes are changing significantly with time, regulation of the carbon flux is central to climate stabilization plans.

Understanding the impact of oceanic events in one region upon processes in another region thousands of miles away is an important research challenge. Basic understanding of regional ocean dynamics has been achieved (in equatorial, mid-latitude, coastal and high-latitude ocean regions) yet knowledge of the couplings among these regions remains rudimentary. The remarkable and publicly recognized success in El Niño prediction paves the way for reliable prediction of climate oscillations at higher latitudes. Oscillations such as the Pacific Decadal Oscillation, the North Atlantic Oscillation and the Antarctic Circumpolar Wave have far-reaching impacts on ecosystems and human activity.

There is strong and compelling evidence of climate-biology-chemistry coupled fluctuations that require a more quantitative understanding. Strong linkages are observed between large-scale variations in climate and populations of marine organisms. The mechanisms involved are still obscure and need intensive interdisciplinary investigation.

The oceans play a key role in the emerging study of the linkages between climate and human health. Although the climate drivers may lie far away, their impacts are felt most dramatically within the coastal zone where human influence is also strong. For example, the linkages between cholera dynamics and the El Niño-Southern Oscillation have been identified in data from Bangladesh, and Indian Ocean temperature anomalies have been used to forecast Rift Valley fever epidemics in Kenya. The use of remote sensing of temperature combined with ocean color provides the key to further progress here. There are numerous instances of possible human health impacts from the changes now being forced in coastal waters, including the long range transport of noxious organisms in ships' ballast water. An opportunity exists to greatly increase our knowledge of pathogens and parasites in the ocean and in identifying, predicting and ameliorating their impacts on human health and the health of marine ecosystems.

It is now possible to create new, science-based observing programs that can meet the climate challenge. Global climate is changing more rapidly than at any time in the past 8,000 years. Our knowledge of ocean biological, chemical and physical fields is growing, but does not yet provide an adequate baseline for observing and predicting this change. The challenge to observe, understand, predict and possibly ameliorate climate change is one of the most fundamental in all the ocean sciences. Advances in technology, if pursued with vigor, can meet the challenge posed by climate change by moving beyond ship observations alone.

Radically new platforms are now available which could address the long-standing shortage of ocean observations. Development of miniaturized optical, chemical and electronic sensors provides the tools for observing the three-dimensional structure of ocean physics, biology and chemistry. Satellite observations of the ocean have led to rapid advances in understanding and will continue to do so. New buoy, satellite, instrumented drifters and remotely operated vehicles, coupled with cabled installations on the seafloor, can help to meet society's growing information needs.

Advances in observing and understanding critically important, abrupt Earth episodes as diverse as earthquakes, eruptions beneath the sea or harmful algal blooms on the surface ocean, will require new modes of long-term observation. There is growing realization that important processes that affect the oceans, and the seafloor below, are dominated by short-lived, episodic events. In order to characterize change in the oceans a systematic long-term observation program is required.

New advances in ocean numerical modeling will greatly enhance understanding and prediction on time and space scales important to society. Crucial physical effects have now been identified that have seriously limited the accuracy of model prediction in the recent past. By taking advantage of rapid advances in computing technology, and of new data streams from powerful observing programs, great advances will be made. Assimilation of new observations, both *in situ* and satellite-based, into computer models is increasingly successful, and is blending with the design of new observational programs. Developments in the theory of time-variable ocean circulation and atmospheric interaction give hope of a deeper understanding of climate change, ecosystem development and the rapidly changing biogeochemical cycles.

Fundamental advances in knowledge of the turbulent mixing of the ocean on all scales will result in new understanding of a host of problems ranging from water-mass conversion to predator-prey interactions. Turbulence at all scales, from millimeters to Earth's radius, acts on physical circulation, climate and ecosystem dynamics. This immense scale range poses significant challenges in both modeling and observation, with notable progress being made at traditional boundaries in scale.

Marine ecosystems are dynamic systems that do not hover about a long-term equilibrium point. New knowledge indicates that marine ecosystems may not be inherently stable, but may be shifted to new states by a range of impacts, including human forcing. Nonlinear interactions among populations, and between organisms and the abiotic environment, can cause surprising changes in ecosystem states over short time periods. Rapid changes from one ecosystem state to another are often caused by strong interactions among organisms in a community, or by multiple weak interactions. Such transitions can be caused by threshold population densities required for successful fertilization, by outbreaks of pathogens and toxic algal blooms, by invasions of exotic species into new habitats or through a sequence of predator-prey interactions. In the absence of a better predictive capability, this fundamentally nonlinear ecosystem behavior poses significant risks for intentional manipulations of the oceans to increase local or regional fertility or to sequester carbon.

Interaction of ocean circulation with behaviorally controlled movements of organisms maintains the spatial connections and persistence of marine populations. Marine organisms both drift with, and swim in, the sea. The understanding of linkages among sub-populations, which both drift and migrate, in a changing ocean circulation is a critical area of study over scales ranging from estuaries to oceanic fisheries. New ocean chemical and molecular biological techniques have revolutionized the study of life cycles in the ocean and allow separate and continuous populations to be discriminated for the first time. The powerful new molecular biological and chemical tools will continue to have enormous impact on the evaluation of marine populations and bring great benefit to mankind.

The complexity of ocean physical circulation may now be approached with sufficient detail and understanding to shed new light on the transport of material, and the fluctuations of ecosystems, important to mankind. Better union between physical forcing functions and biological and material processes promises rapid advancement in understanding. The ability to incorporate biological and chemical processes into the new class of ocean models will advance rapidly, with great benefit to the study of important ecosystems.

An increased knowledge of the linkages at ocean margins is essential to guide human development in coastal regions. There is clear evidence of the regulation of water, chemical and sediment fluxes by mankind on a scale that now equals or exceeds the fluxes of nature. The impact of natural and anthropogenic material fluxes on the coastal margins is an important area of study. Material and population exchanges among land, estuaries, continental shelves and the deep ocean are essential to the biology, physics, geology and chemistry of the ocean.

Evidence for the existence of bacterial communities deep below the ocean floor is an extraordinary and exciting indication of the extremes of life. Yet, the size of this population, its rate of growth and its unusual adaptations remain highly controversial and an important and challenging area of study. The nature and extent of biological activity within ocean crust, and the impact of these sub-seafloor communities on physical, chemical and biological processes is one of the most exciting, new frontier areas of ocean-science research.

Fluids flowing through and below the seafloor influence a wide range of microbial and geological processes. This field offers important opportunities for discovery in microbial ecology as well as the impact of biotic and abiotic processes on the alteration history of oceanic crust, the composition of the oceans and the thermal evolution of the lithosphere. The role of fluids (water and magma) in geochemical cycling between the solid earth, hydrosphere and atmosphere will be another important new avenue of research in the coming decade.

Advances in geophysical imaging, geochemical tracing and geodynamical modeling, coupled with the renaissance of deep ocean drilling technologies, will lead to major breakthroughs in understanding Earth's dynamic evolution. These technical advances set the stage for major scientific advances in understanding oceanic upper mantle dynamics and the role of the oceanic lithosphere and mantle plumes in the circulation and compositional evolution of Earth's mantle, crust, oceans and atmosphere.

The transition from passive observation of the ocean to deliberate, controlled experiments with tracers has been of enormous benefit. The changes in the ocean created by mankind can now not only be detected and assessed, but the insights gained have led to an important new class of small-scale, deliberate tracer and biogeochemical perturbation experiments. A notable challenge is to use both intentional and unintentional manipulations to better understand the biogeochemical workings of the oceans. Particularly important is the need to develop means of scaling results from spatially and temporally limited manipulations to provide insights and confidence limits for larger-scale oceanographic processes.

An important task in the next decade will be to train a new generation of ocean researchers who must have the skills for mastery of their discipline, and yet be imbued with the knowledge and desire to solve interdisciplinary problems of high order. Understanding of the coupled physical, chemical, biological and geological processes occurring in the oceans will require novel, interdisciplinary research approaches, and the training of a new generation of students who are able to effectively attack problems from a truly amalgamated perspective.

RECOMMENDATIONS

Access to the Sea

A substantial, well-coordinated, multi-agency fleet replacement plan is needed to maintain United States leadership in sea-going capabilities in the coming decades. Almost all the fundamental discoveries in ocean science have come from direct observation of the sea with increasingly sophisticated research and drilling vessels that can support advanced scientific teams. Maintaining a modern, well-equipped research fleet is the most basic requirement for a healthy and vigorous research program in the ocean sciences. The research fleet must include a range of capabilities including highly specialized vessels, such as sophisticated drillships and their associated tools, which allow sampling deep below the seafloor. The anticipated mix of research demands large vessels capable of mounting interdisciplinary studies both near to and far from land and supporting remotely operated vehicles and submersibles as well as versatile small- and intermediate-sized ships for studying the coastal ocean.

New Technologies

The profound impact of new technologies for executing novel experiments and for capturing new data from the ocean is a theme that runs throughout this report. Their success justifies a vigorous effort in technology development, implementation and support in all areas of ocean science. Ships alone do not represent scientific capability; it is the novel ocean-observing technologies installed and operated on and around them that brings the needed advances. These new tools include sophisticated, remotely operated and autonomous vehicles, powerful acoustic and photographic imaging and mapping systems, and physical and chemical sensors for making *in situ* measurements. The information revolution is driving sophisticated data assimilation, and advances in computing have led to the development of more realistic and reliable ocean models. The technological feasibility of using a combination of fixed and mobile observing systems to study change in the ocean, and on the seafloor below, has been demonstrated. These successes allow articulation of needed technological capabilities:

- **Solving the problem of ocean sampling on space and time scales appropriately tuned to the process being investigated is key to success.** 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, new sampling and observation strategies, and new technologies must be developed to adequately measure and understand these processes.

- **New fixed (cabled or moored buoy) and mobile (ROV, AUV, drifter) ocean-observing systems are an essential complement to ships and satellites, and must be deployed if critical events are to be captured.** No one technological approach can give synoptic, high-resolution or continuous views of the whole ocean or the seafloor below. This new class of platforms is recently available. There is an urgent need to develop sensors and sampling strategies to optimize the mix of these new platforms with ships and remote sensing in removing critical data gaps.

- **Long-term monitoring of the ocean is essential for basic research. The need for long-term monitoring is highlighted by every scientific theme presented in this report.** The lack of extensive, more-or-less continuous time-series measurements in the oceans is probably one of the most serious impediments to understanding of long-term trends and cyclic changes in the oceans and in global climate, as well as episodic events such as major earthquakes, volcanic eruptions or submarine landslides. We recommend strong support for the development, deployment and maintenance of long-term observing systems.

Data Assimilation

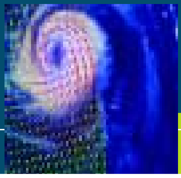
A continuing effort must be made to improve databases, and ready access to these databases, by the scientific community. The continued improvement in the techniques and mechanisms by which data are collected, controlled for quality, made available to researchers, analyzed and archived must go hand in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

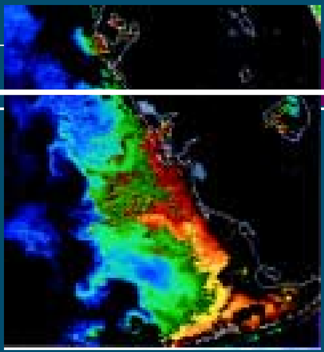
Model Development

A continued emphasis is needed on the development of models in all their many applications, and a special effort is needed in developing models that link different parts of the ocean system. Almost all oceanographic research themes involve some aspect of computer modeling. The need for model development and improvement can only grow in the future. Models have proved essential in determining the relative importance of variables in complex, nonlinear systems that have multiple positive and negative feedbacks. Linked models that tie together, for example, physical, geological, biological or 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 both designing observation strategies and in evaluating outcomes.

Perturbation Experiments

A vigorous exploration of a new class of controlled perturbation experiments could provide unique scientific information not available through conventional observation. A powerful new class of highly successful ocean perturbation experiments has emerged that holds great promise. For example, deliberate tracer injections have enabled observations of mixing. Other examples include geochemical tracers to determine flow paths and fluxes of submarine hydrothermal systems. The controlled fertilization of areas of the surface ocean with truly minute amounts of iron can be used to study both CO_2 uptake and ecosystem dynamics and is a new variant of a well-known type of perturbation experiment in agriculture and ecology. The establishment of marine reserves, or sanctuaries, is also a form of perturbation experiment that deserves to be carefully exploited with predictive models and time-series observations.





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