Oceanus

REPORTS ON RESEARCH FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

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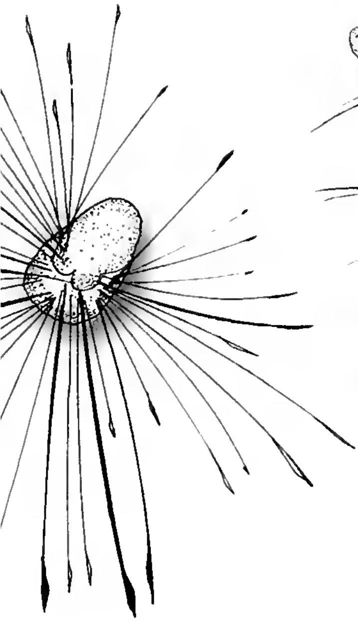
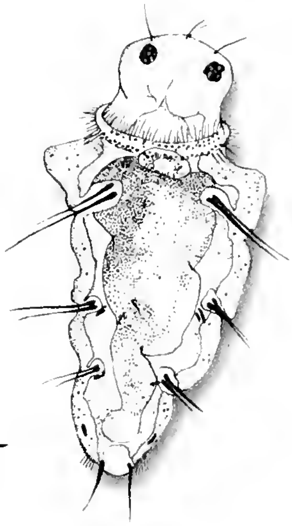
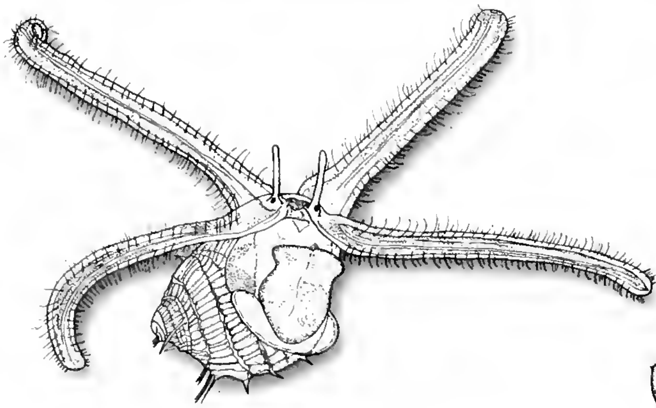
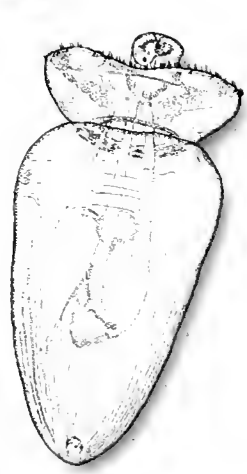
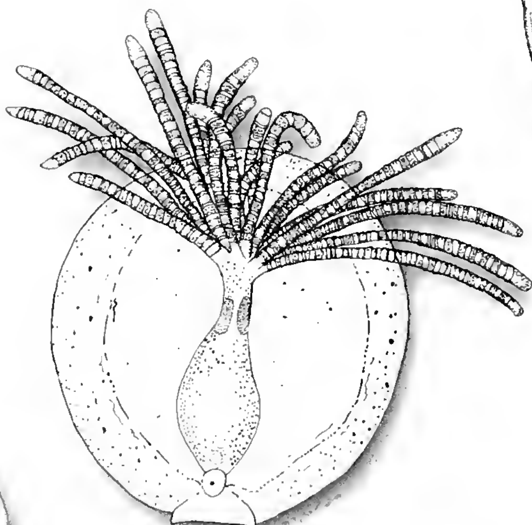
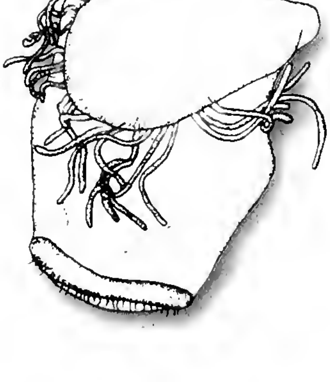








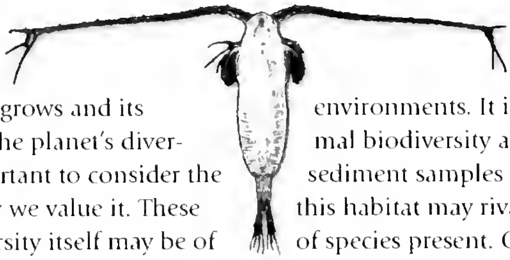




Marine Biodiversity II

Biodiversity & the World Ocean

Comments from the Editor



As Earth's human population grows and its activities profoundly affect the planet's diversity of animal life, it is important to consider the significance of biodiversity and how we value it. These are not easy judgements. Sheer diversity itself may be of inestimable value as a foundation for a healthy planet and human well-being. Many ecologists now believe that richly diverse ecosystems are more resilient and better able to recover from such stresses as drought or human-induced habitat destruction than less diverse systems. Some describe biodiversity as nature's insurance policy against catastrophe, because greater diversity offers a range of pathways for primary production and ecological processes such as nutrient recycling—if one pathway is damaged or destroyed, alternatives are available to allow the ecosystem to continue functioning at its usual level.

The human activities that most affect biodiversity—coastal development, logging, transport of species from one habitat to another in ships' ballast tanks—are unlikely to stop. But we can *think* about what we do, and we can make some choices. We can learn more about the great web of life and its interconnectedness in order to make *wise* choices. Earth would be a lonely place for humans without a bird call, the hope of seeing a fish jump, or just knowing that elephants and tigers still roam free (tigers only in Asia, not in Africa as we mistakenly suggested in the introduction to the last issue—thanks to the sharp-eyed reader who pointed out our error!).

This issue of *Oceanus* continues our celebration of the sea's wonderful diversity of life. Marine Biodiversity I (Vol. 38, No. 2) discussed new insights on marine bacterial diversity and on midwater animals that live in a vast, stable habitat that is one of our planet's least explored environments. It included an update on marine mammal biodiversity and took us to the deep sea, where sediment samples collected in the 1980s revealed that this habitat may rival tropical rainforests in the numbers of species present. Our authors also described new molecular techniques that offer powerful tools for probing biodiversity, discussed how scientists go about estimating diversity, and described a national research agenda on marine biodiversity drawn up by a special National Research Council Ocean Sciences Board committee.

This issue's authors continue the Marine Biodiversity theme by offering a look at the myriad forms of phytoplankton and zooplankton and at the salt marsh habitat, and introducing taxonomists, those important people who undertake species description.

The Biodiverity sidebars and the second section, called "WHOI and the World Ocean," offer you a peek into the laboratories of the Woods Hole Oceanographic Institution (WHOI). The authors discuss a wide variety of oceanographic topics that range from robots to fish feeding behavior and air-sea interaction to sound reception in seals. Geographically, the articles range from Block Island Sound to the the Arabian Sea and the western equatorial Pacific.

At any given time, there are some 350 research projects underway at WHOI as each scientist pushes the marine frontier, describing an organism that is new to human knowledge, elucidating a puzzling process, or developing a new research technique. They travel the world to work aboard the research vessels of the United States and other countries, attend international meetings, and work with colleagues on today's major marine questions. Here they share their work with you.

—*Vicky Cullen*

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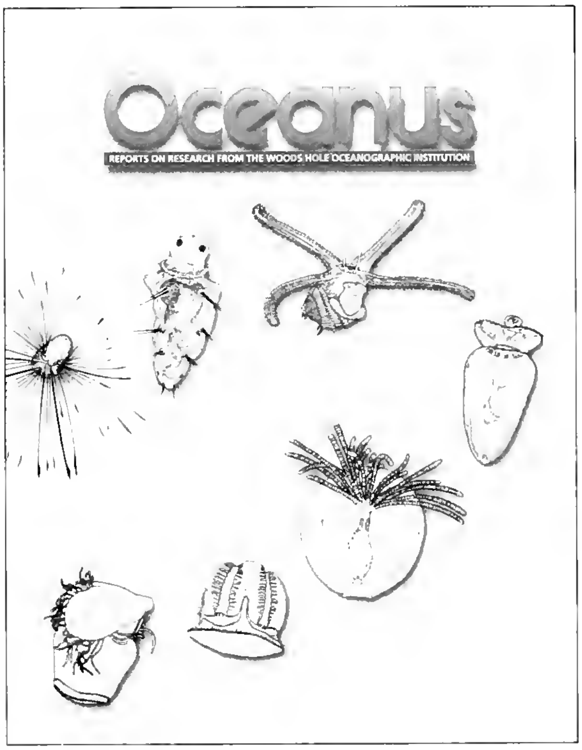

Marine Biodiversity

WHOI and the World Ocean

Editor: Vicky Cullen • Designer: Jim Canavan
Woods Hole Oceanographic Institution

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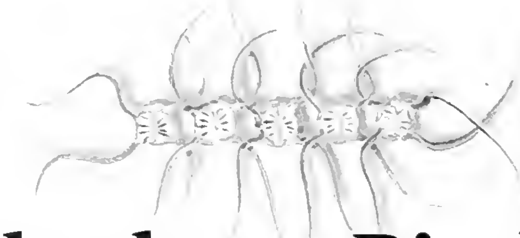


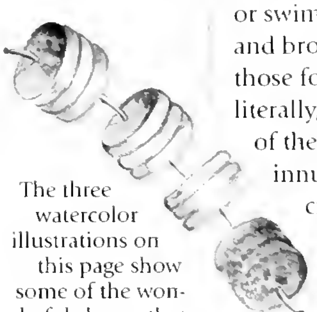
Phytoplankton Biodiversity

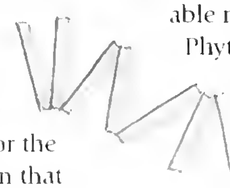
Boxes, Spheres, Spirals, and Sunbursts

*Ecosystems, like well-made airplanes, tend to have redundant subsystems and other "design" features that permit them to continue functioning after absorbing a certain amount of abuse. A dozen rivets, or a dozen species, might never be missed. On the other hand, a thirteenth rivet popped from a wind flap, or the extinction of a key species involved in the cycling of nitrogen, could lead to a serious accident.—Ehrlich and Ehrlich, 1981**

Anya M. Waite
1992-94 Postdoctoral Scholar, 1994-95 Postdoctoral Fellow

Slip a drop of seawater under a simple light microscope, and the diversity of marine phytoplankton is spectacular: Thousands of tiny boxes, spheres, spirals, and sunbursts float or swim by, packed with bright green and brown pigments analogous to those found in land plants. These are, literally, the "plant" plankton, the base of the oceanic food chain and prey for the innumerable small animal plankton that cruise the coastal ocean to feed. Each phytoplankter is a single cell that grows and divides into two new cells, eventually populating whole sectors of the world ocean. They range in size from the ultra-phytoplankton, about one-tenth of a millimeter in diameter, down to the pico-plankton that are thousands of times smaller. Their predators include every herbivore, from small, cup-shaped protozoans that pull individual picoplankton into their hairy mouths, to crustacean copepods and larval fish that can bite through whole chains and clusters of ultra-phytoplankton.





The three watercolor illustrations on this page show some of the wonderful shapes that diatoms exhibit. They are normally visible only under a microscope.

The key to the overwhelming diversity of marine phytoplankton may be the highly variable marine environment in which they live. Phytoplankton have responded in dozens of different ways over evolutionary time to alternating patches of vigorous ocean mixing and calm waters, to the patchy abundance of predators, and to changing vertical gradients in the light intensity and nutrients they need for growth. Each species has capitalized on different combinations of these factors, selecting a unique shape, size, and physiology to maintain survival. Some phytoplankton can be extremely flexible in their response to the environment, developing tolerance to a wide range of possible habitats, while others' requirements are highly specific. The result is an enormously diverse species assemblage.

The logical outcome of this is that any changes in the ocean that create uniform conditions across wide areas, including heavy nutrient inputs from sewage or large-scale industrial pollution, can potentially reduce the diversity of species within them. The Ehrlichs tell us in *Extinction* that a rich biodiversity increases the ability of ecosystems to respond to, and recover from, such stresses. Essentially, we depend on high biodiversity for protection from extreme biological responses to external forces, including pollution, overfishing, and global warming. But our understanding of exactly how these responses occur is rudimentary at best. Our intuitive grasp of the ecology of marine species is often poor compared to our feel for more familiar terrestrial

D. Wall

Resting cysts of the toxic dinoflagellate *Alexandrium tamarense*. These dormant cells overwinter in the sediment like seeds, germinating as waters warm to provide the inoculum for "red tide" blooms. They measure about 30 by 50 microns.

*Ehrlich, P.R. and Ehrlich, A.H. 1981. *Extinction: The causes and consequences of the disappearance of species.* Random House, New York.

Dean Jacobson

A mid-ocean phytoplankton sample shows the diversity in form that typifies oceanic regions. The large cell in the center is a dinoflagellate, about 80 microns long, in the genus *Ornithocercus* (ornitho=bird, cercus=tail). The large appendages may act as flotation devices or may increase cell surface area to enhance nutrient uptake.

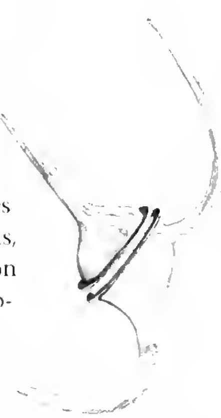
systems, and phytoplankton's tiny size compounds the problem.

However, as soon as we begin to explore how different phytoplankton species have adapted to their environment, we can see how intricately these organisms are caught up in the global scale of the marine ecosystem. These adaptation differences are typified by two of the major groups of large ultra-phytoplankton, the dinoflagellates and the diatoms, which have each adapted very differently to ocean dynamics. Dinoflagellates are one of the most unusual groups in the world ocean. Up to one-fifth of a millimeter in diameter, with a membrane-covered organic shell, they sport a pair of beating flagella that make them twist and spin as they move. "Dinos" prefer calm water where they can gather at the surface to photosynthesize in bright sunshine and then plunge down to imbibe the rich nutrient cocktail available in deeper waters. Though mostly solitary, dinos can form chains of cells that swim as a unit, their longitudinal flagella beating in tandem.

Dinoflagellates have a unique form of highly abundant DNA that remains condensed into chromosomes throughout their cell cycle. Some species form a pigmented structure that is almost the perfect analog of a human eye—but thousands of times smaller—formed within a single cell. There are species of dinoflagellates that are partially or wholly herbivorous, sometimes actually eating other phytoplankton many times their size by impaling them, enveloping them in a membrane, and siphoning out the contents.

Most famous of the dinos are the species that gather in high densities at the surface to form what is known as a "red tide." Many of these red tide species are known for their potent toxins, which can become concentrated when they are eaten by filter-feeding shellfish, eventually poisoning human consumers as (for example) Paralytic Shellfish Poisoning, or PSP.

Such spectacular and lethal events do not characterize all species of di-

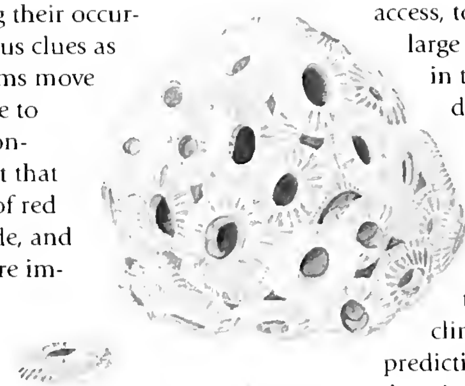


These shapes are characteristic of dinoflagellates. Note the flagella.

1 millimeter equals one-thousandth of a meter (.03937 inch)

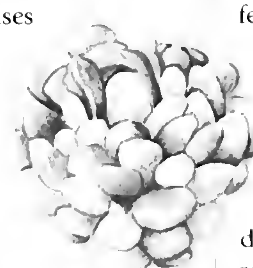
1 micron equals one-thousandth of a millimeter

noflagellates, but monitoring their occurrence on a global basis gives us clues as to how these diverse organisms move around the world in response to changes in the marine environment. Some scientists suggest that the frequency and intensity of red tides are increasing worldwide, and it is becoming more and more important to understand and monitor the dynamics of individual species. The increase in red tides is cited as evidence for an increase in coastal pollution, since calm, nitrogen-rich waters are ideal for dinos' growth. In addition, the recent appearance of northern species in southern waters highlights the necessity of monitoring ship ballast water for the errant phytoplankton species that can be transported thousands of miles and emptied into foreign harbors to find new habitat. Even a quick evaluation of dinoflagellate ecology leads us to the conclusion that understanding their biodiversity is of immense practical importance.



Coccolithophores are single-celled plants whose cell walls are embedded with small calcareous plates or coccoliths. These are magnified about 4,000 times.

The diatoms are another sort of organism altogether. With their heavy glass shells (called frustules), diatoms can sink quickly out of the surface layer once they have used up all the available nutrients, waiting in dark cool water to be mixed upward again, in some cases on an annual cycle. Diatoms generally depend on vertical mixing to reach the ocean surface again, and keep themselves there only when conditions are favorable to their growth, by pumping an internal vacuole full of substances lighter than seawater. During favorable periods, they maximize their growth rates to optimize the limited time they spend at the surface, and can reach high densities, especially in the springtime coastal ocean. Some predators depend entirely on this early spring bloom as a food source, and the timing of the bloom can influence the survival of larval fish and copepods critical for the next year's productivity. Once they sink to the seafloor, diatoms can become food for invertebrates that in turn feed everything from fish to gray whales. When diatoms reach the bottom in such numbers that they cannot all be eaten, they accumulate in ocean sediment layers, leaving a record of their pulse of productivity for thousands of years. With them is preserved a chemical signature that can tell scientists a great deal about how the phytoplankton grew.



It is this record that paleoceanographers try to access, to understand more fully how large pulses of production occurred in the past. Understanding how different species react to changing climatic conditions, how they are transported to the seafloor, and what factors govern their preservation in the sediments are critical for the reconstruction of Earth's climate history—and thus for predictions of global climate change. For example, scientists use the chemical composition of organisms found in sediments to make estimates of the carbon dioxide concentrations that existed thousands of years ago. Recent work by Jack Baldauf at Texas A & M University highlights how mass sedimentation of diatoms can actually disrupt the sedimentary fossil record, inserting large mats of diatoms between the more regular layers of sediment. Heated debate also continues on exactly what source of carbon phytoplankton use for growth. Different carbon sources can radically alter how the chemical makeup of phytoplankton is related to the carbon dioxide concentration of the ocean in which they grow. Thus back-calculating to reconstruct Earth's ancient climate becomes a complicated matter indeed. Work at the Alfred Wegener Institute in Bremerhaven, Germany, by Ulf Riebesell, suggests that different diatoms actually use different carbon sources—with an enormous potential impact on the sort of signature the cells preserve. The species diversity of diatoms has also changed over the ages, and these changes themselves may yield clues as to how the upper ocean has changed over the ages.

But as it turns out, the tools scientists use to determine species composition are only now reaching a stage where we can fully understand how individual species evolve and how they are related to one another.

Diatoms' dependence on ocean mixing to reach the surface has led them to develop a wild assortment of morphologies to catch the currents. This allowed scientists initially to describe thousands of living diatom species and categorize them in a framework that identifies how each species is related to another based on their morphology alone. The frustule itself can be fantastically ornate, covered in patterned ridges and pores in geometric designs. One group, the *Chaetoceros* species (see illustration above headline on page 2), are known for the formation of enormous glass spines with sharp triangular barbs extending out from their frustules. In numerous species, many cells adhere to one another, forming long chains and clusters. Chains can take on a spiral form, be elongated and flex-

Photos courtesy Don Anderson

Illustrations by E. Paul Oberlander

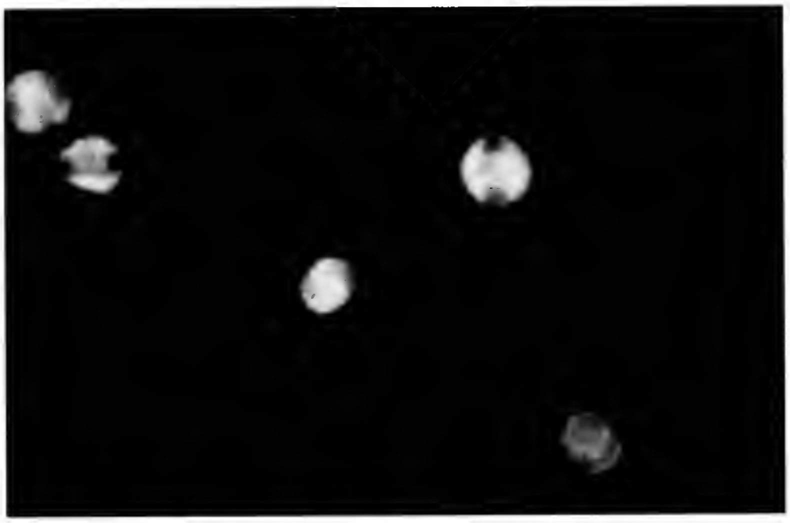
ible, or entirely rigid. Some clusters are spherical and held together with a dense mucus that fills the spaces between the cells.

Recently however it has become clear that classifying such organisms on the basis of morphology alone can be misleading. The definition of a species was originally developed for land mammals for whom that definition of a species holds fairly well (very generally, any two animals that cannot mate successfully with each another are considered different species). Mammals multiply exclusively through sexual reproduction, allowing them to shuffle their genes with each generation and potentially create an enormous amount of genetic diversity within a population. However, phytoplankton are single cells that multiply through binary fission. They shuffle genetic material only rarely, and each generation is a clonal replicate of the last. Then, when they do actually have sex, the mating patterns can be complicated. In some cases, two similar strains can exchange genetic material with each other, but only one of them will successfully mate with a third, and so on. The same cells grown under different conditions can change the length of their spines and chains and even the shape of their frustule. So understanding what a species means becomes difficult even though the idea of a "species" is one of the most recognizable and practical units of biodiversity for field biologists.

New techniques are revolutionizing the study of phytoplankton biodiversity. Optical techniques like flow cytometry, which allow scientists to count and characterize hundreds of thousands of phytoplankton cells per minute, are being perfected in the laboratory of Rob Olson. In 1988 Olson and Penny Chisholm (MIT) discovered a new and highly abundant group of picoplankton in the open ocean called "prochlorophytes." These previously unknown organisms are now understood to be responsible for a huge fraction of the productivity of open ocean systems.

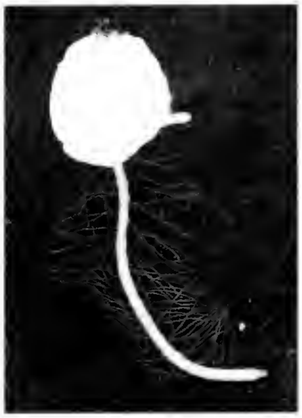
Newly available molecular techniques that probe the DNA of each organism offer the possibility of looking directly at the organisms' genes to see exactly how related they are. Important work has been done in the laboratory of Don Anderson on dinoflagellates and by Michelle Wood (University of Oregon) on diatoms. Such work shows further that identical-looking species may not actually be the same, or that species whose appearances are entirely different may in fact have close ancestors. It is to these techniques, especially when used in combination with the more classical morphological analyses, that we will look for future progress in understanding phytoplankton biodiversity. Understanding the growth responses of the myriad species, and indeed, identifying important species both morphologically and with DNA fingerprinting, will be critical to a better understanding of such global processes.

Anya Waite completed her WHOI postdoctoral appointments in September 1995 and took a position as Research Fellow at the School of Biological Sciences in Wellington, NZ. Her oceanographic wanderings have taken her to the coasts of Australia, Canada, Spain, Germany, Chile, the US, and most recently New Zealand. In addition to working in science, she has published magazine articles on science and the environment as well as classical music reviews. She is, she says, also currently at work on the Great Canadian Novel!



Photos by David Kulis

The top photo shows *Alexandrium tamarense* cells from the Gulf of Maine probed with a small fragment of DNA coupled to a fluorescent compound that glows bright green under an epifluorescent microscope. A specially synthesized DNA probe is binding to specific sequences on RNA inside the cells, allowing the observer to easily identify them. The bottom photo shows a negative result when the same probe is used on a strain of *Alexandrium tamarense* from Europe. Even though the cells in the two photos are considered the same species and would look the same under a normal, bright-field microscope, the DNA probe easily distinguishes them on the basis of genetic differences.



Protozoan Grazers

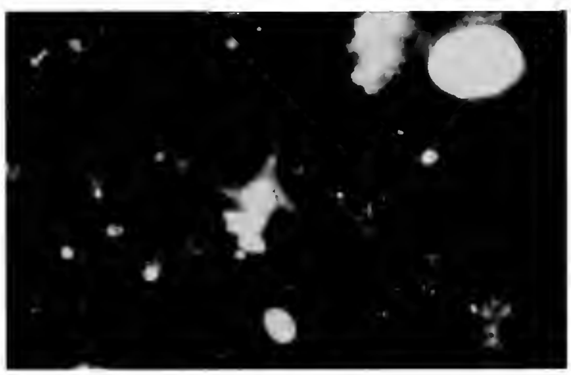
They May Influence the Biological Availability of Iron to Phytoplankton

James W. Moffett
Associate Scientist, Marine Chemistry & Geochemistry Dept.
Katherine A. Barbeau
MIT/WHOI Joint Program Student

Iron is an essential micronutrient for marine life, yet it is highly insoluble in seawater. Dissolved iron concentrations in the oceans are exceedingly low, and much of the iron that is present occurs in relatively refractory forms, such as very fine particles (colloids), which are difficult for organisms to assimilate. Some scientists propose that, in many areas of the world's oceans, iron may actually limit the growth of marine phytoplankton, the primary producers in the oceanic water column. Biologists and chemists at WHOI and elsewhere are currently investigating the mechanisms phytoplankton use to obtain the iron they need. Considerable attention is focused on how the refractory forms of iron, including iron oxide minerals and iron bound to dissolved or colloidal organic matter, are converted into forms that phytoplankton can use. Two processes that have been particularly well-studied are the dissolution of refractory iron by sunlight through a photochemical mechanism, and the dissolution of refractory iron by siderophores, compounds produced by bacteria and some phytoplankton.

Recently, research in our laboratory has identified an additional mechanism that may contribute to the supply of available iron for phytoplankton. We are studying how heterotrophic nanoprotozoans, tiny grazers less than 20 micrometers in size, can influence iron chemistry in seawater. These organisms are ubiquitous, essential components of marine food chains: The principle fate of bacteria in seawater is to be consumed by nanoprotozoans! Protozoans engulf their prey and incorporate it into a food vacuole within the cell where it is subjected to harsh chemical treatment involving digestive enzymes and acidic conditions. We are interested in how this process can affect particulate forms of various trace metals, including iron, by accelerating dissolution processes that would not occur significantly in seawater. Nanoprotozoans could be particularly important since they ingest particles in the 0.2 to 1 micrometer size class, which represents a large pool of particulate metals.

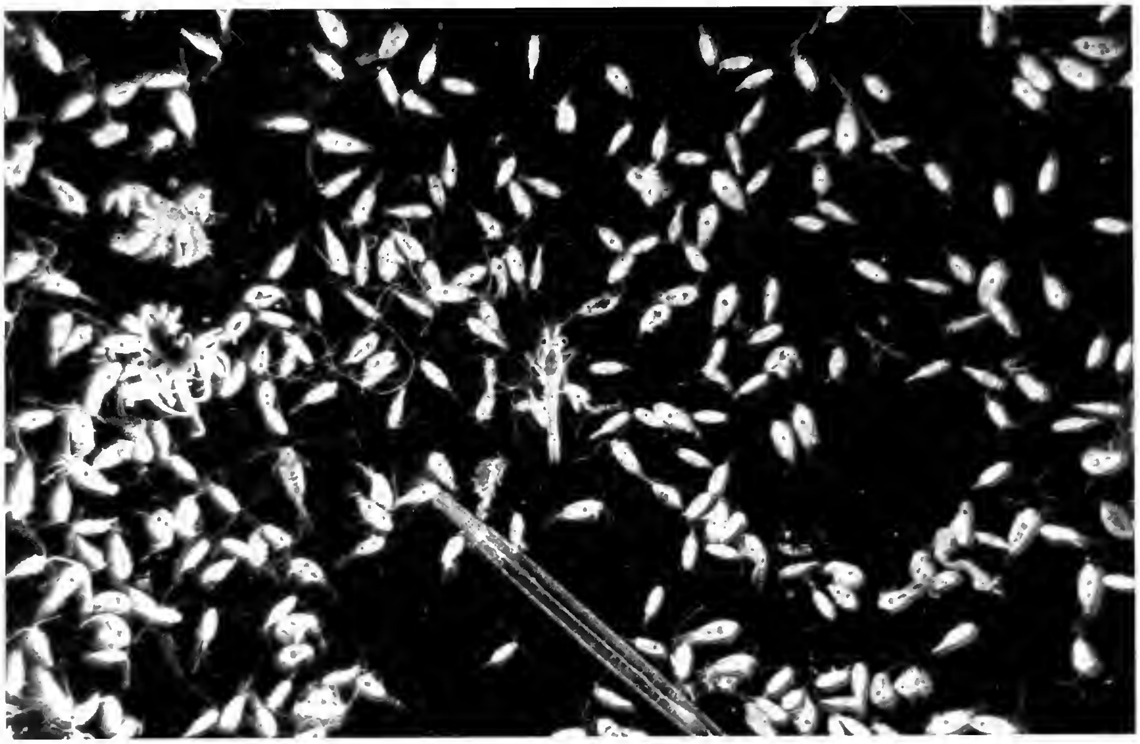
Our laboratory studies of what happens to colloidal iron oxides ingested by protozoans show that protozoan grazers can greatly accelerate the production of dissolved and chemically reactive iron from colloidal iron oxides in seawater. Most significantly, our research indicates that protozoan grazers can convert refractory colloidal iron oxides into a form of iron that is biologically available to diatoms, a major group of phytoplankton. Given the abundance of protozoans in the upper ocean, this may be a significant mechanism for the production of biologically available iron. The next step will be to conduct field experiments, studying colloidal iron dissolution in freshly collected seawater samples spiked with tracers and incubated under a variety of conditions. We will also study the ability of protozoans to dissolve atmospheric dust particles, which are a primary source of trace metals to the open ocean.



Photos by Ee Lin Lim

Epifluorescence micrograph of a diversity of protists found in coastal waters of Vineyard Sound (above) and scanning electron micrographs (top) of two species of heterotrophic protists under high magnification. These organisms are less than 20 microns in size.

Protozoans may play an even wider role in ocean chemistry. Through their digestive process, they create a chemical "microenvironment" very different from that of bulk seawater. Marine chemists are only beginning to study processes occurring within this microenvironment that may include dissolution of anthropogenically produced particles such as fly ash, transformation of organic contaminants, and production of new colloidal phases.



Tom Kleindinst

Zooplankton, primarily copepods, collected in May 1996 on Georges Bank during a Global Ocean Ecosystems Dynamics Program (GLOBEC) cruise. Copepods are the most plentiful members of the zooplankton and possibly the most abundant animal group on earth.

Zooplankton Diversity

A Bizarre—and Changing—Array of Life Forms

Cabell S. Davis
Associate Scientist, Biology Department

Carin J. Ashjian
Postdoctoral Scholar, Biology Department

Philip Alatalo
Research Associate, Biology Department

The great majority of animal species in the sea spend at least part of their lives as members of the plankton. The term plankton comes from the Greek word "planktos," meaning "drifter," so plankton are generally small, passively drifting creatures (although some, like the jellyfish, can be quite large). The animal or *zoo-* (pronounced zoh) plankton include the young life stages of fish, crabs, lobsters, barnacles, clams, starfish, conchs, squid, and nearly all other groups of familiar sea animals (except mammals) as well as other less familiar, but abundant, groups.

Many larval forms look nothing like their parents—for example, who would guess that the larva at right would metamorphose into an adult crab? Remarkable adaptations in body form among the plankton result in a bizarre array of life forms.

Tom Kleindinst

Larval crab (zoea stage) collected with a plankton net off the WHOI pier during May 1996. The larva is about 2 millimeters long.

Not all zooplankton are larvae of familiar larger animals. In fact, the zooplankton is dominated numerically, and in total mass, by animals that spend their entire lives as plankton and are unfamiliar to most people. Such animals are termed holoplankton, while the temporary residents of the plankton (such as the larval forms) are called meroplankton.

Tom Kleindinst

Adult female (larger) and male of the copepod species *Pseudodiaptomas coronatus*. The female is about 1 millimeter long. In this species, the female carries her eggs in a clutch attached at the base of her body.

One group of holoplankton, the copepods (coh' pah pods), deserves special mention. Copepods are more numerous than any other group of animals on earth (with the possible exception of roundworms), yet the average person has never heard of them. The number of copepods residing under each square meter of sea surface can range from one thousand to over one million (and they are also abundant in freshwater environments). Since the ocean covers 70 percent of the earth's surface, or 137 million square miles, there are about one quintillion (10^{18}) copepods on earth!

In addition to being plentiful, copepods are Earth's fastest animals for their size. Using a high speed video microscope mounted on an ROV

The copepod *Calanus finmarchicus* collected on Georges Bank (May 1996). This species dominates the zooplankton mass in late spring and is the main food of many species including cod and haddock larvae as well as north Atlantic right whales (see box below). This specimen is shown in the characteristic feeding posture with its long antennules spread far apart to detect oncoming predators.

Tom Kleindinst

(Remotely Operated Vehicle), researchers have found that copepods can swim at speeds of 500 body lengths per second. By comparison, a cheetah would have to run 2,000 miles per hour to attain the same relative speed. In fact, an F-16 fighter jet only moves about 50 body lengths per second. Even more amazing is that copepods achieve their rapid movement through water, a much heavier and more viscous medium than air.

Copepods need to be able to move fast to avoid their countless predators. While feeding, copepods assume a characteristic posture (photo at left): With their long antennules extended widely apart, they often hover or cruise slowly as they filter food from the water with their feeding appendages. The antennules detect vibrations generated by oncoming predators, which, if too close for comfort, cause the copepod to cease feeding and initiate an escape response. To escape, the copepod rapidly folds its legs and antennules down along the sides of its body, creating a streamlined bullet shape and propelling itself instantly through the water to a location several body lengths away. Copepods can repeat this escape response several times in a row before tiring.

Gulf of Maine Physics

Linking Large and Small Marine Animals

Ari W. Epstein
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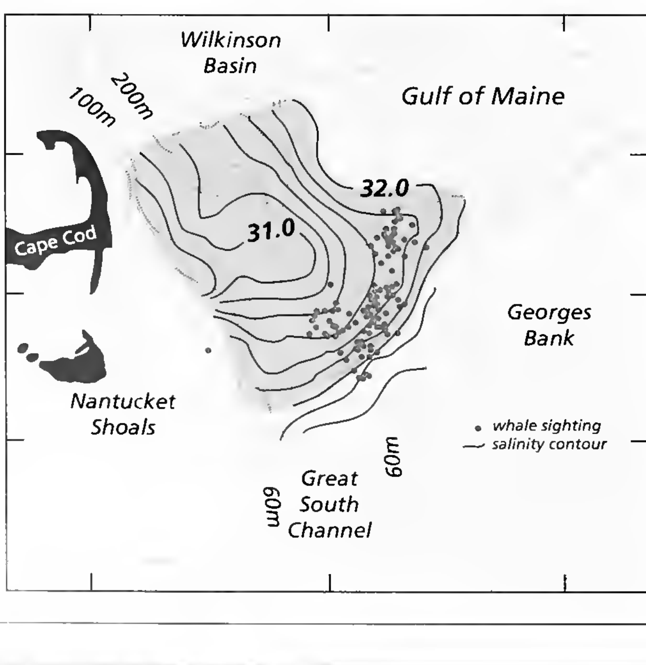
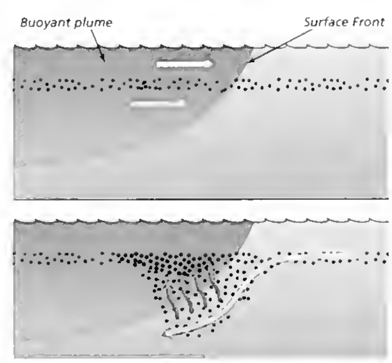
Every spring, most (and perhaps all) of the right whales known to exist in the North Atlantic—about 300 to 350 individuals—migrate to the shallow Great South Channel of the Gulf of Maine, which divides Georges Bank from Nantucket Shoals. There they feed for about two months on dense patches of the zooplankton species *Calanus finmarchicus* (photo above). The existence of these dense patches is extremely important to the whales: Right whales feed by swimming with their mouths open, filtering prey out of the water with their baleen. Because of the additional hydrodynamic drag involved, open-mouth swimming costs a whale much more energy than closed-mouth swimming, and so unless there is a very high concentration of prey in the water, the whale can actually *lose* energy by attempting to feed. Right whales may not feed at all during the winter, so it is crucially important for them to find a large number of dense *Calanus* patches during the spring and summer.



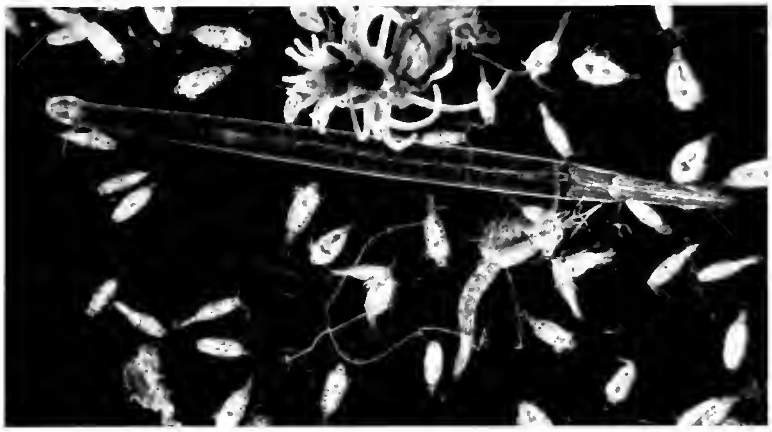
Jack Cook

What causes dense clumps of *Calanus* to form in the Great South Channel? One clue may be found in the figure at left, which shows large numbers of whale sightings (red dots) and hence, probably, *Calanus* patches, just at the edge of a plume of relatively



Jack Cook

(Top) A buoyant plume advances over heavier water in which plankton are distributed in a thin layer. (Bottom) Plankton that are swept under the plume seek their preferred depth, swimming upward to join plankton already within the plume. Eventually a dense patch of plankton accumulates at the edge of the plume.

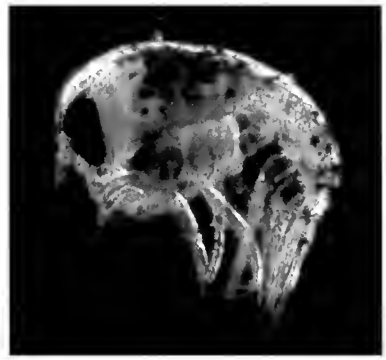


Tom Kleindinst

The large, straight, clear animal is a chaetognath or arrow worm about 2 centimeters long. It was collected on Georges Bank in May 1996.

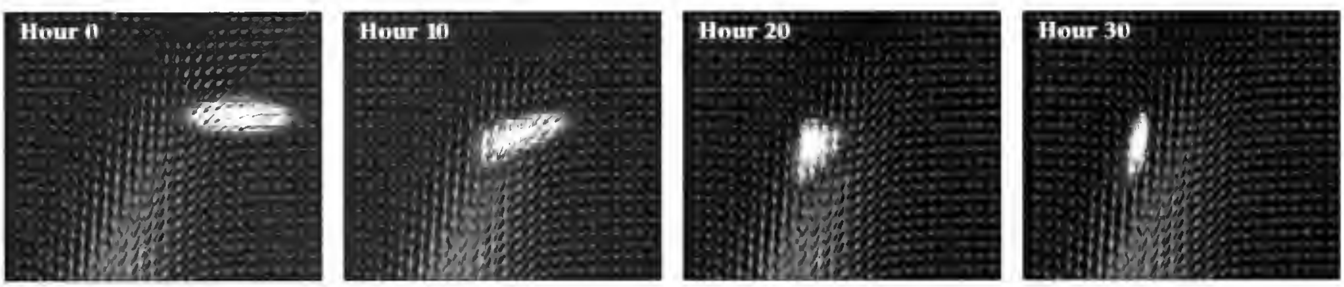
Given the small size of most zooplankton, the environmental conditions in the microworld they inhabit are very different from those in the human macroworld. If we humans were to magically shrink to copepod size, microworld water would feel viscous or syrupy due to the physical properties of water at those small scales. It would cling to us as we tried to swim through it. However, when a body moves very rapidly, the fluid medium appears to become thinner or less viscous, and copepods take advantage of this physical phenomenon. When feeding, they swim slowly in "thick water," but, when escaping, they move so rapidly that the effective drag on their bodies is greatly reduced.

In addition to copepods, a great number of other species spend their entire lives as plankton. Some examples include arrow worms (or chaetognaths—see photo above) and amphipods (photo at right), which are voracious predators on copepods and larvae of larger species. A group of marine snails, the pteropods (photo overleaf), have adapted to life in the sea by using a "foot" to swim rapidly through the



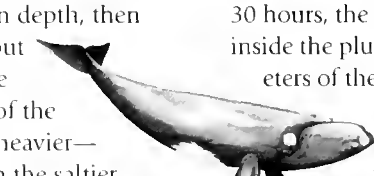
Tom Kleindinst

A 1-centimeter amphipod. Note the large scythelike appendages used to capture prey.



A computer simulation of the process shown in the page 8 figure. Red arrows represent water velocity (the plume is at the left side of each panel). At hour 0, a diffuse blob of plankton is just outside the plume. Over time, the plankton are swept below the plume (hour 10), swim up into the plume water (hour 20), and form a highly concentrated clump there (hour 30)

fresh water spreading across the channel (darker blue). Plumes like this one, which is probably the result of freshwater runoff from rivers in northern New England, are thought to form every year. Whales are often observed at or near the edge of the plume. The figure at left shows one way in which the advance of such a plume could create a dense clump of plankton. If the plankton prefer to live at a certain depth, then initially they might be distributed evenly (but sparsely) in a thin layer at that depth. As the relatively fresh—and thus buoyant—water of the plume advances over the saltier—and thus heavier—water in the channel, plankton contained in the saltier water will be swept beneath the plume. Then the plankton will be below their preferred depth, and so they may swim upward into the plume water, joining the plankton that are already there. As the plume continues to advance, a dense clump of plankton will form at its leading edge.



The figure above shows the output from a computer simulation of this process. The red arrows represent the water's velocity; the buoyant plume is on the left side of each panel. At first (Hour 0), a sparse blob of "plankton" is seen just outside (to the right of) the plume. After 10 hours of model time, the plankton are beginning to be swept under the plume water. By 20 hours of model time, the plankton have swum up into the plume, and the concentration of plankton in the center of the blob is beginning to rise (orange region). After 30 hours, the blob is compressed into a dense clump just inside the plume's leading edge. By varying certain parameters of the computer model—the animals' swimming speed, the shape of the plume, etc.—it may be possible to test whether this process could indeed form the kinds of dense *Calanus* patches seen in the Great South Channel. If so, it may then be possible to determine which factors are most important in forming the dense patches—and thus in providing the North Atlantic right whale with its all-important feeding grounds.

Much of the material for this article was extracted from the author's MIT/WHOI Joint Program Ph.D. thesis, completed in 1995. The work was funded in part by the National Science Foundation and the National Oceanic and Atmospheric Administration.

Illustrations by E. Paul Oberlander

water. Larger plankton include euphausiid shrimp or krill, which feed on phytoplankton as well as on smaller zooplankton. The jellyfish also are considered planktonic since they drift with ocean currents, and there is a wide variety of these important predatory species (see *Oceanus*, Fall 1991).

The species diversity of zooplankton is far too great to characterize adequately in this short article. Nearly all major groups of animals on earth are represented in the zooplankton. An important exception is the insects, which contain three-quarters of the known animal species (and over half of all known species) and are almost entirely terrestrial. The majority of the approximately 400,000 noninsect animal species live in the ocean and have planktonic life stages.

Tom Kleindinst

A pteropod (2 millimeters).

In addition to the large number of species, the mass of zooplankton in the ocean is huge: If all the zooplankton were strained from the ocean and spread across the continental US, the resulting layer would be several feet thick, and over half of it would be made up of copepods. This tremendous mass of zooplankton replaces itself several times per year through normal birth and death processes; together with the even larger mass of the phytoplankton, it forms the base of the ocean food web.

The ocean provides a natural incubation system for the eggs and larvae of sea animals, so that parental investment in caring for young is not necessary for most marine species. Eggs and larvae grow and develop while drifting passively with the ocean currents. Although this natural incubator often provides adequate food, the young animals usually suffer great losses to a variety of predators. To offset these losses, many marine species lay huge numbers of eggs, though only a few individuals survive to adulthood. The number reaching adulthood can vary by a factor of 10 to 100 from one generation to the next, leading to large variations in adult

Carin Ashjian

The Video Plankton Recorder (VPR), an underwater video microscope, was attached to ROV *Jason* to measure the swimming behaviors of zooplankton in the ocean. The frame on the front of *Jason* supports three cameras and two high-speed strobes for measuring 3-D movements of plankton. Here *Jason* is being deployed on Georges Bank during the GLOBEC study.

Tom Kleindinst

The VPR can also be configured for towing behind a ship to make high-resolution, rapid measurements of zooplankton distribution together with physical variables over large distances in the ocean. Two cameras and a strobe are mounted on the "arms." Environmental sensors are located along the body and vertically on the tail. Here Cabell Davis, left, and Robert Granucci prepare the VPR for a cruise aboard R/V *Oceanus*.

population size. The factors affecting survivorship from egg to adult (termed "recruitment") remain poorly understood and are the subject of intensive study in biological oceanography.

In order to understand what controls the diversity of zooplankton species, scientists are examining how individual animals and populations of selected species interact with the physical, chemical, and biological environment of the sea. Since plankton, by definition, drift with the ocean currents (though many can swim short distances up and down toward the surface or bottom), understanding the causes of their population fluctuations requires knowledge of the fluid motions of the sea. Teams of physical and biological oceanographers are cooperating to examine the interaction between zooplankton swimming behaviors and transport by currents. Other investigators are studying the rates of feeding, growth, reproduction, and death for selected species in order to understand how these rates vary with temperature, food, and predator abundance. New instruments, such as the Video Plankton Recorder (VPR), developed by Cabell Davis and Scott Gallager, are bringing new insights to studies of the interaction between zooplankton and their environment.

By determining the fundamental processes controlling zooplankton populations, scientists will gain a better understanding of fishery yields, the consequences of pollution, and the global carbon cycle. As an example, Global Ocean Ecosystems Dynamics (GLOBEC) program investigators are studying the factors controlling recruitment in cod and haddock populations on Georges Bank, an important fishing ground off the New England coast. Populations of these fish species often are dominated by one or two outstanding or "bonanza" year classes. Studying the basic physical and biological interactions in the plankton that lead, in some years, to outstanding survival of larval cod and haddock will help scientists better understand and predict fluctuations in commercial fish stocks. More generally, studying these basic processes in the plankton will provide fundamental new insights into the ecology and diversity of life in the sea.

Cabell Davis, Carin Ashjian, and Phil Alatalo work together with Scott Gallager and Andy Girard in their quest to understand the dynamics of marine zooplankton populations. This work often requires long hours at sea, sampling through the night with the Video Plankton Recorder. Because their shipboard lab space is always shrouded in darkness or bathed in red light to prevent glare on the video monitors, shipmates have dubbed the VPR group "the vampires." By the end of their watch, however, the say they feel more like zombies than vampires.

Cabell Davis, left and Scott Gallager analyze VPR tapes in WHOI's imaging and visualization center.

Tom Kleindinst

Measuring Diversity of Planktonic Larvae

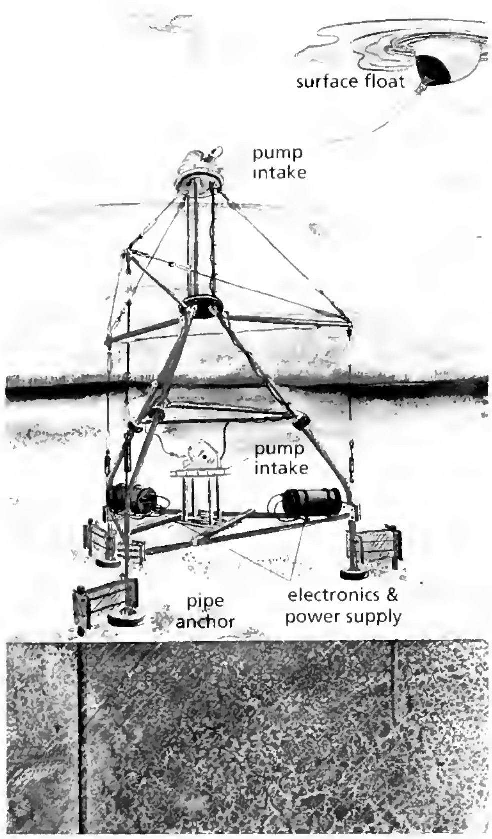
Catch 'Em (and Identify 'Em) If You Can

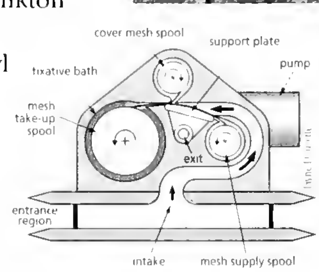
Elizabeth D. Garland
WHOI/MIT Joint Program Student, Biology Department
Cheryl Ann Butman
Associate Scientist, Applied Ocean Physics & Engineering Dept.

Imagine several million microscopic organisms living in a single glass of seawater! This is the emerging picture of planktonic ecosystems in coastal environments. The density of organisms is overwhelming, and most species have unique roles within the ecosystem. Planktonic larvae of benthic (seafloor-dwelling) invertebrates—such as worms, clams, and snails—are only temporary members of the plankton, so their importance in pelagic ecosystems is often overlooked. However, given that many larvae reside in the water column longer than the life spans of many copepods, which are considered a part of the "permanent" plankton, larvae can be important members of the planktonic food web. Larvae also colonize new habitats and replenish adult populations on the bottom. Thus, larvae can influence the diversity of both planktonic and benthic ecosystems.

Unlike the larger permanent zooplankton, many of which may be identified to species in acoustical or optical images (see *Oceanus*, Spring/Summer 1995), planktonic invertebrate larvae are so small (0.01–0.05 centimeters, 0.004–0.02 inches) and the morphological differences between them so subtle, that they must be collected directly to be identified to species. One new instrument, the Moored, Automated, Serial, Zooplankton Pump (MASZP), was designed by co-author Cheryl Ann Butman and WHOI engineer Ken Doherty to make moored, time-series collections of planktonic larvae at time and space scales comparable to data taken, for example, by moored current meters.

Traditional zooplankton pumps were tied to a ship's power source because they used very high intake velocities to overcome escape responses of organisms that, ironically, were escaping from flow disturbances created by the pumps! To decrease the intake velocity and thus the power needed for long-term, moored collections, the MASZP "sneaks up" on the larvae before they are able to initiate an escape response. Each discrete water sample is filtered over a portion of mesh, which is covered by another piece of mesh, and the two strips are wound together on a spool residing in a preservative bath for *in situ* storage. The sampling schedule and volume are programmed beforehand on an internal computer. The material collected is later washed from the mesh, and the larvae are sorted from the samples by hand for microscope identification—a very time-consuming and costly process.





The Moored, Automated, Serial, Zooplankton Pump tripod can be placed in water depths up to 1,500 meters to collect planktonic larvae for hours to months. The diagram shows the collection path and apparatus.

To expedite sample processing, we are working with a biotechnology company, Hydros Inc. (Falmouth, Massachusetts), to develop species-specific "immunofluorescent" markers for larval identification. Immunological techniques for recognizing species in mixed populations require the presence of unique, diagnostic "signature proteins" within a given larval species. These proteins, called *antigens*, when injected into a vertebrate host (such as a rabbit or goat), trigger an immune response, and antibodies are released in the host to confer immunity to the antigen. The host antibodies can be isolated, purified, and tagged with fluorochromes—color-coded molecules that can be detected visually. When fluorochrome-labeled, species-specific antibodies are added to a mixed species assemblage in a MASZP sample, the antibodies recognize and bind to all individuals of that species, and they fluoresce as tiny dots in the sample dish. We hope to develop a palette of species-specific immunofluorescent probes that will paint the various species different colors in MASZP samples. A color image-analysis system will then count the number of each color-coded species from a video taped image of each sample. Thus, we are approaching the complete automation of sampling and identifying planktonic larval distributions!

Salt Marshes

They Offer Diversity of Habitat

John M. Teal
Scientist Emeritus, Biology Department

Salt marshes look remarkably uniform: Low and flat, they are a luscious green in the spring and summer, tan to brown in fall and winter. The marshes have been studied intensively, in part because their higher plants and animals exhibit a remarkable *lack* of diversity. Though they therefore seem unlikely topics for an *Oceanus* issue on biodiversity, there are three good reasons to discuss salt marshes in this context:

- Although the visually dominant higher plants and animals lack diversity, the smaller salt marsh animals and plants are more diverse than meets the eye.
- Systems with low biodiversity have values that are important to acknowledge and appreciate.
- Salt marshes make an important contribution to *habitat* diversity.

More Species Diversity Than Meets the Eye

Spartina alterniflora (cord grass) dominates the regularly flooded parts of the salt marsh, and *Spartina patens* (salt hay) and *Distichlis spicata* (spike grass) dominate the higher marsh, which floods monthly, but only at the higher tides. Other higher plants growing in the marsh, such as *Salicornia* (pickleweed) and *Limonium* (marsh lavender), are typically both rare and inconspicuous. As a result, the salt marsh resembles a lush lawn where the mowing has been neglected.

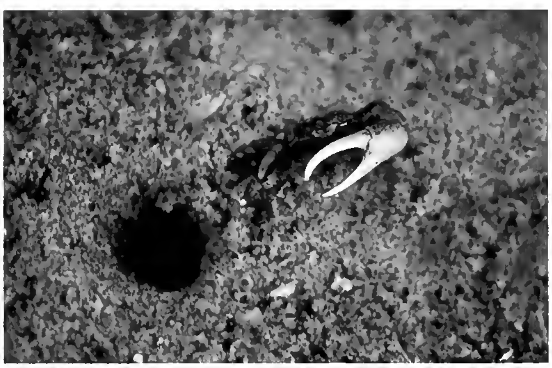
Fiddler crabs are the most readily visible, and typical, marsh animals. A closer look reveals marsh mussels, snails, amphipods, and isopods, but there are only a few species of each. However, a look at the microscopic level reveals the level of diversity more apparent in other systems. Nematodes, soil mites, epibenthic algae, protozoa, insects, and spiders are all abundant and diverse in salt marshes. Unfortunately, we know less about these salt marsh organisms than

Above, a mallard swims among the *Phragmites* grasses of a Cape Cod marsh. At left, the elusive clapper rail exhibits a distress display among salt marsh grasses. Below, the photographer catches a typical fall salt marsh vista in Mashpee, Massachusetts.

Typical salt marsh inhabitants include, from the top, an American egret, a salt marsh periwinkle, a fiddler crab, a cluster of ribbed mussels, and a killifish.

Ned Manter

Brian Howes



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John Teal

we know of similar animals in dry land environments. We have yet to describe many species taxonomically (that is, we cannot even give them a name) or scientifically define their relationships to the other parts of the marsh ecosystem. These animals are generally terrestrial in their evolutionary origin, but have adapted to periodic contact with salt water.

The water-dwelling organisms are very much a part of the salt marsh even though they may not come in direct contact with its grassy parts. The diversity of the aquatic fauna and flora is very similar to those in the estuarine waters, which inundate the marsh with every tide. There are a few fishes, such as mummichogs, that live primarily in marsh creeks and that forage above the flooded surface of the marsh at high tide. But most marsh fishes are either "tidal migrants" or "nursery species" that live in estuarine and coastal waters as adults. The larvae and young of many nursery species spend the warmer portions of the year entirely within the marsh, move to coastal waters in the autumn, and return to the marsh as adults only as high-tide predators. The tidal cycle controls the size of marsh fish, offering the largest only a few hours when the water is deep enough for them to forage successfully. In other words, our view of the diversity of marsh fishes depends not only upon which species we are watching, but also on the stage of the tide, the season of the year, and the size of the individuals.

Marsh Values Beyond Diversity

Given that the salt marsh ecosystem is of varying and relatively low diversity depending on the group of organisms being examined and the time of measurement, salt marshes are not one of the marine ecosystems especially valued for the sake of species biodiversity. They are valued, however, because they are productive, they provide high quality habitat, and they are beautiful. Salt marshes produce both higher plants and algae in abundance, and this plant production supports high levels of animal growth and reproduction.

Marshes are the seasonal or year-round habitat for birds, reptiles, and fishes. Several threatened species, such as the black rail, marsh harrier, and short-eared owl, are among the birds dependent upon marshes, and the diamond-backed terrapin also depends upon the salt-marsh habitat.

Production of fish and shellfish is probably the principal reason most people value salt marshes. Twenty years ago, we believed that the export of large quantities of detritus, mostly disintegrating bits of plants, to the estuaries was the main way that salt marshes supported fish production. By the early 1990s, most marsh ecologists have come to understand that the nursery and refuge values of salt marshes are more important. With their shallow pools and coarse, creek-bank grasses, marshes provide hiding places for small fishes and refuge for young fish from larger ones. A little fish in shallow water is vulnerable to tern and heron predation, but this source of danger is overshadowed by that from the likes of large, hungry bluefish. The high volume of food for fish in the marshes and the summer warmth of marsh waters combine with the refuge factor to allow young summer resident fishes to survive better and grow faster that their less fortunate, coastal-water brethren.

Terri Corbett

Scientists at the Woods Hole Oceanographic Institution have conducted studies in the Great Sippewissett Salt Marsh of Falmouth, Massachusetts, for several decades. Since 1970, they have maintained plots for studies of chronic nutrient enrichment that help to answer questions about the impacts of increasing development in adjacent coastal watersheds and of nitrogen loading in coastal ecosystems as nearshore populations grow around the world. This 26-year data set, which began with a project to look at possible use of salt marshes for tertiary sewage treatment, is thought to be the longest continuous investigation of experimentally manipulated marsh plots. The photo shows a WHOI group fertilizing the Sippewissett Salt Marsh plots.

Salt Marsh Ecosystem Diversity

The real value of salt marshes to biodiversity is the variety of habitat and landscape they provide at the edge of the sea. Instead of an abrupt change from land to water, the marshes provide buffers between the two environments, a gradual transition.

The marsh is partly terrestrial in the higher, more landward portions. Here the grasses are submerged only a few times a month. Insects, mites, and spiders find it relatively easy to make use of this part of the marsh. Voles make their runs under the thick cover of salt hay grasses and dine on the tender portions of their stems and leaves. Black rails, unbirdlike in their behavior, live rather like mice, dashing about so hidden in the grasses that they are usually detected only by their calls during the mating period. Land birds come into this part of the marsh to feed, as do rabbits and deer (and cattle and sheep if they are allowed). The effect of the infrequent but regular tidal flushing creates a natural meadow, keeping upland vegetation out, but allowing land animals to make use of it most of the time.

The regularly flooded part of the marsh is covered by coarse cord grass whose stems are far enough apart for small fish and even little squid to swim in at high tide to hide and feed. While many insects make use of this low marsh, marine-type animals such as crustacea, snails, and mussels are more common.

Grass along the tidal creeks may grow several meters tall. Its tops are woven into nests by marsh wrens, and clapper rails forage and hide in the dense growth. Raccoons come out to feed on shellfish and crabs and sometimes make nests of the tall grass where they rest during high tides.

Finally, we come to the mud flats and tidal creeks. Though there are no higher plants growing up into the air, algal production is high and widgeon grass grows in some of the pools. This is the special habitat of marsh fishes and shrimps and of many clams, crustaceans, and worms, all supported by the high vegetative production and shallow waters. The shallows also provide hunting grounds for ospreys, herons, egrets, terns, and gulls.

Ned Manter

Marshmallows often ring salt marshes. In colonial times, the roots of these flowers were boiled to make a candy—hence the modern marshmallow

Salt marshes integrate land and sea. They give a diversity to the landscape that changes with the tides, becoming alternately landlike and marine. They harbor coastal highways for animals from both land and sea, and provide refuge for creatures from both worlds. The combination of conditions creates high productivity to support animals from ocean and land, but especially the animals from the sea.

This marsh ecosystem supports species diversity in neighboring environments, and herein lies the principal diversity value of the salt marsh.

John Teal, who retired as a Senior Scientist in the WHOI Biology Department in 1994, began intensive salt-marsh research while working at the University of Georgia marine laboratory on Sapelo Island many, many years ago. There he was so isolated from most marine environments, but surrounded by marshes, that he had little choice but to get mired down in them. He says he has been stuck ever since!

Neotanais micromorpher Gardiner, a pericarida about 20 millimeters long belonging to the order Tanaidacea from the deep sea, is an example of deep-sea species discussed in this article.
Illustration by L.F. Gardiner

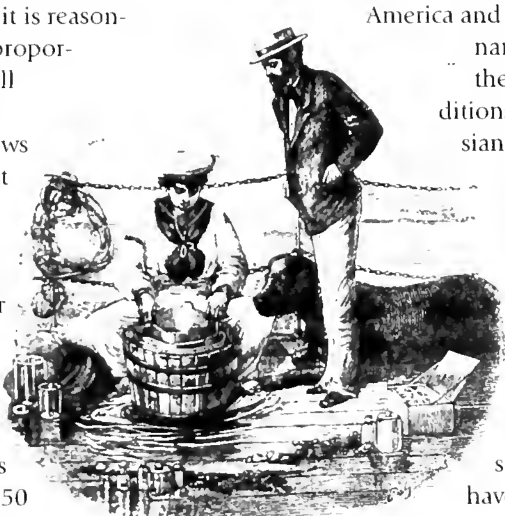
Describing Diversity

Too Many New Species, Too Few Taxonomists

Rudolf S. Scheltema
Senior Scientist, Biology Department

Marine biodiversity can be defined as the number of species occurring within a circumscribed region or habitat. Consequently, for biodiversity to be understood, taxonomists—scientists who describe and name species—must have a chance to examine the flora and fauna of the region or habitat under consideration.

Since the oceans occupy approximately 71 percent of the earth's surface it is reasonable to suppose that a large proportion of the world's species will be found there, and indeed existing evidence already shows that the oceans harbor a great variety of life. Two-thirds of the world ocean floor is deeper than 2,000 meters (1.2 miles). First evidence for the very great biological diversity of these abyssal depths has come within the past 30 years with the introduction of finer mesh screens (less than 0.5 millimeters, 1/50 inch) for separating organisms from the bottom sediments that most species inhabit (see The Deep Sea: Desert AND Rainforest, Oceanus Fall/Winter 1995). Since most organisms from samples taken before 1965 were lost through the coarse mesh screens previously used, analysis of these samples gave a grossly distorted estimate of diversity in the deep sea. It now has become apparent that the deep sea bottom fauna includes untold numbers of heretofore undescribed species, many never previously encountered. Recent estimates of the numbers of deep-sea species vary a hundredfold, from hundreds of thousands upwards to ten million.



Screening a deep-sea bottom sample on the *Challenger* Expedition (1872-1876)—the seaman does the work while the scientist and the Newfoundland dog watch.
From *Report on the Scientific Results of the Exploring Voyage of HMS Challenger, 1873-76* Vol. 1, First Part. Published by Order of Her Majesty's Government, 1885

Yet the study of this newly discovered diverse fauna has only just begun. There are on the shelves of laboratories and museums of North America and Europe thousands of unnamed species collected within the past three decades on expeditions of American, French, Russian, and British research ships.

For example, among the superorder pericarida, a major taxon that includes most of the minute bottom-dwelling crustacea of the deep sea, 69 percent among those found in the western Atlantic during the past 30 years are newly discovered species. Though some of these have received attention, most remain to be named and described. Among the 236 species of polychaete worms from the deep western North Atlantic, 64 percent are undescribed, and among bivalve mollusca, one of the better known groups of the deep-sea benthos, 105 new species (about 43 percent of all species

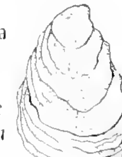
What is Taxonomy, Anyway?

taxonomy—1. the science of classification; laws and principles covering the classifying of objects **2.** *Biol.* a system of arranging animals and plants into natural, related groups based on some factor common to each, as structure, embryology, biochemistry, etc.: the basic taxa now in use are, in descending order from the most inclusive, *phylum* (in botany, *division*), *class*, *order*, *family*, *genus*, and *species*

—Webster's New World Dictionary

Genus and species are the terms commonly used to designate animals. A complete heirarchical schema for the American oyster distributed along the east coast of the United States is:

Phylum: Mollusca
Class: Bivalvia
Order: Pteriodea
Family: Ostreidae
Genus: *Crassostrea*
Species: *virginica*



The American oyster is referred to as *Crassostrea virginica*: *Crassostrea* is the genus of a group of oysters; *virginica* is the specific name that designates a particular kind or species of oyster. Although they may vary significantly in size and shape, all members of the species *Crassostrea virginica* exhibit certain characteristics. In the case of *Crassostrea virginica* these include a left or attached valve larger than the right, production of large numbers of eggs (up to 50 million) that are externally fertilized, muscle scar colored deep purple, and a long, strongly curved beak.

The taxonomist who describes a species selects and deposits an individual specimen, called a "type," in a museum for the reference of other taxonomists. There is, however, more to taxonomy than accurately describing and naming species. The taxonomist also makes inferences about speciation and evolutionary relationships.

Illustration by Rudolf S. Scheltema

collected) have been described over the last 20 years. Only one-third of the collected species of Aplacophoran molluscs have been named and described even though they are an important component of the deep-sea fauna and often appear among the ten most abundant species.

Meanwhile, the number of undescribed new species grows unrelentingly with each additional deep-sea dredge sample—and biologists estimate that a total area of only 500 square meters (635 square feet) of the world ocean floor has been sampled!

Shallower regions off continents are also undercollected in many parts of the world. Recent reports indicate that one-third (124 species) of all polychaete worms collected from Georges Bank are undescribed and unnamed, while a small sample of coral sand from a fringing reef off one of the Hawaiian Island (about as much as fits in six one-quart pickle jars) produced 112 new species (78 percent of all species present in the sample). Ninety-two percent of the flatworms (123 species) collected from two locations on Australia's Great Barrier Reef were new. Shore collections made in tropical lagoons, from coral reefs, and even from rocky shores continue to yield large numbers of new unnamed species.

The question now arises: "Is it really necessary to name and describe every species in order to understand the biological diversity of a particular fauna?" The structures of different bottom communities exhibit striking differences. For example, on the bottom of Buzzards Bay near Woods Hole, Massachusetts, samples from 19 meters depth yielded 79 species of macro-invertebrates exceeding 0.5 millimeter in size. If the species in a sample are ranked in the order of their abundance, two, a bivalve (*Nucula proxima*) and a polychaete worm (*Nephthys incisa*), make up three-quarters of the total individuals. If the next five most abundant species are included (namely all species that exceed 1 percent of the total sample) then 91 percent of all individuals will be included. Thus the remaining 72 species make up only 9 percent of the fauna.

Isabelle P Williams

Deep-sea sediments are placed in fine-mesh-bottomed pans, and running water washes the mud away, leaving its inhabitants on the screen.

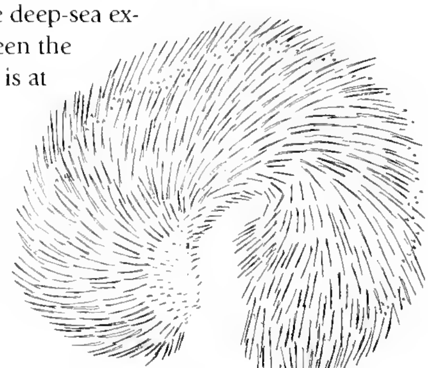
Compare these percentages with those from dredge samples taken at abyssal depths averaging 2,000 meters off the east coast of the United States. A total of 798 species were collected, approximately ten times the number found in Buzzards Bay. The most abundant species in the abyssal samples is a polychaete worm, *Aurospio*

Rudolf S. Scheltema

Scientists screen a deep-sea bottom sample aboard *Atlantis II* during the summer of 1966. The scientists do the work—no seaman is in sight. Times have changed!

dibranchiata, which on average is only 7.1 percent of the total number of individuals. The first two most numerous species make up only 11.7 percent of the fauna, in contrast to Buzzards Bay where they make up three-quarters of the total sample (76 percent). The first seven species in the deep-sea sample still make up only 28 percent of the total, whereas in Buzzards Bay they represent 91 percent of all individuals. Consequently, to understand the biodiversity of the deep-sea fauna, it will be necessary to identify more species than in shallow coastal waters in order to understand how the community functions. Indeed, some species that occur in small numbers may nevertheless have a profound effect on the community.

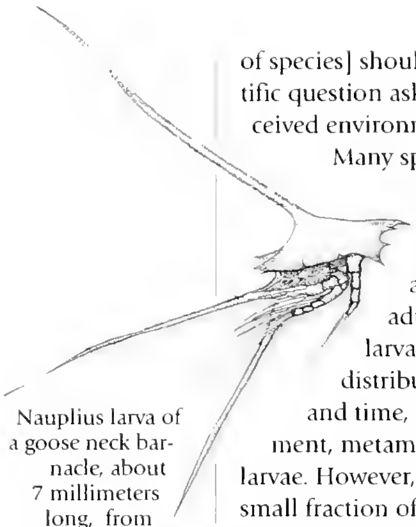
How many species must we describe? There is, of course, no simple answer. In the deep sea, where biodiversity is unusually great, it is necessary to know as much of the fauna as practically possible since no species there is overwhelmingly dominant. In the deep-sea example above, the difference between the most abundant and rarest species is at most only 7 or 8 percent. By contrast, in shoal waters this difference may exceed 90 percent. Understanding Marine Biodiversity, A Research Agenda for the Nation, published in 1995 by the National Academy Press (see Oceanus, Fall/Winter 1995), observed, "The level of investigation of biodiversity [i.e., the number



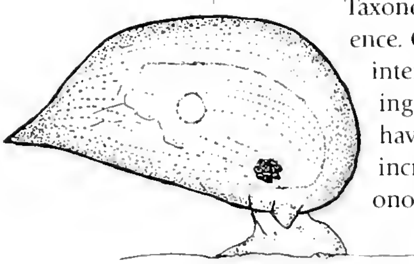
An unpublished new species of mollusc, about 3 millimeters long, belonging to the class Aplacophora. Aplacophora differ from other molluscs, such as bivalves and snails, in that they are worm shaped and covered with calcareous spicules. Most species of Aplacophora occur in the deep sea. Illustration by Amélie Scheltema.

of species] should be dictated by the basic scientific question asked, and the urgency of the perceived environmental threats...."

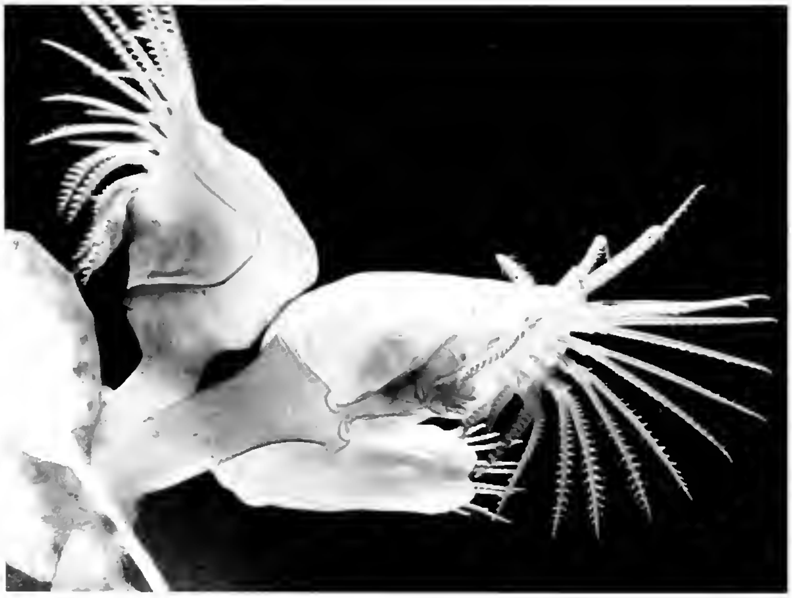
Many species found in marine inshore waters are known to have a planktonic, free-drifting larval stage that differs radically from and is not readily related to its adult parent. The importance of the larval stage is that it may influence the distribution of a species both in space and time, according to success in settlement, metamorphosis, and survival of the larvae. However, the larvae are known for only a small fraction of all species. Among the 380 most common species listed in Key to Marine Invertebrates of the Woods Hole Region (R. I. Smith, ed., Systematics Ecology Program, Marine Biological Laboratory, 1964) the larval forms of only 96 species have been described. Consequently, three-fourths of the most common species can be recognized only by their adult forms. This presents the taxonomist with a perplexing problem—it is rather like knowing the identity of a butterfly but not of its caterpillar!



Nauplius larva of a goose neck barnacle, about 7 millimeters long, from open waters of the tropical South Atlantic. After passing throught several naupliar stages by shedding its outer skeleton, a penultimate, nonfeeding 1-millimeter cyprid larva stage (drawing below) is attained. Illustrations by the author.

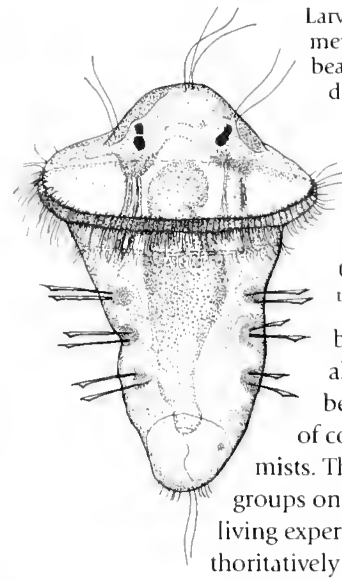


Taxonomy is a precise descriptive science. Over the past half-century both interest in and opportunities for training and advanced graduate study have declined catastrophically. The increase in gray heads among taxonomists is alarming; for many animal groups there are but few experts actively working with or able to authoritatively describe and identify species. Species identification among many marine



Two adult goose-neck barnacles are shown attached to a plant and about 1.5 times life size. Barnacles of this type are often found attached to flotsam and jetsam or drifting algae in the open sea. Feeding is accomplished by the segmented appendages—legs used to rake in particulate food.

Gray Museum, MBL, Woods Hole



Larvae (about 1 millimeter long) of the beautiful "feather-duster" tubeworm *Spirobranchus giganteus* inhabit hermatypic corals of the Great Barrier Reef of Queensland, Australia. Illustration by the author.

benthic groups is almost impossible because of the lack of competent taxonomists. There are for some groups only two or three living experts who can authoritatively describe, name, and identify species; for others there are none at all! As older taxonomists retire, there are no new young biologists to replace them.

Recognition of this problem by the National Science Foundation has resulted recently in the initiation of a new program, "Partnership for Enhancing Expertise in Taxonomy" (PEET), designed to support research on poorly known groups of organisms and to train a new generation of taxonomists in such taxa. The grants provide for funds to publish monographs and to computerize data bases for the dissemination of information and aids to identification. Though modest, the efforts of PEET are appropriate and important steps toward recognizing the need for trained taxonomists in the "pursuit of biodiversity."

Rudolf S. Scheltema

An adult of "feather-duster" tube worm, shown about life size and removed from its calcareous tube, exhibits striking coloration that may vary from scarlet to deep blue.

Understanding the sea's biodiversity will require a greater effort in order simply to describe and name species. This information is a prerequisite for understanding biological processes in the ocean, and it is the taxonomist who must provide this knowledge.

Rudy Scheltema has been a biologist at WHOI since 1960. His studies on the life histories of invertebrates have led him to consider the importance of passive dispersal to the biogeography and evolution of benthic invertebrate species and taken him to remote parts of the world, most recently tropical South Pacific islands and Antarctica

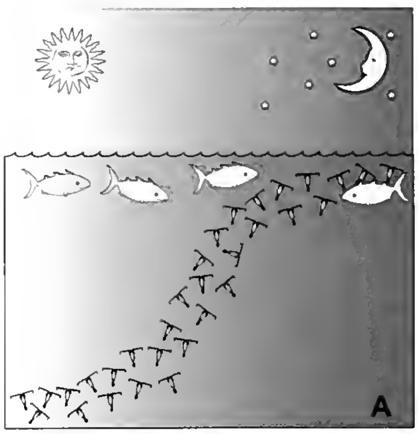
Diel Vertical Migration in Zooplankton

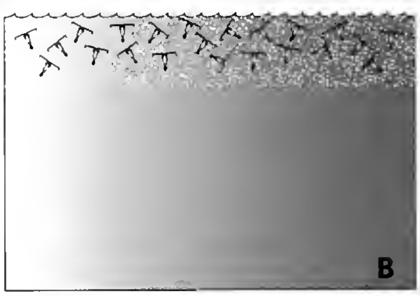
Trade-offs Between Predators and Food

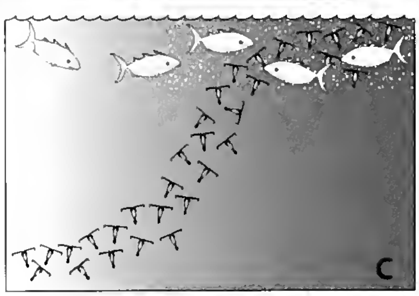
Stephen M. Bollens
Assistant Scientist, Biology Department

Why do so many aquatic organisms, including zooplankton, undertake vertical migrations of tens to hundreds of meters between deep, darker waters during the day and surface waters at night? The answer to this question has long eluded scientists, despite the fact that this behavior, known as diel vertical migration, has been recognized for over a century as one of the most conspicuous and important types of animal migration on earth. Recent experiments undertaken with collaborators at the University of Washington and the Max Planck Institute of Limnology shed new light on this enigmatic phenomenon.

We borrowed from a theory developed primarily by terrestrial ecologists that predicts individual animals should select a habitat or set of habitats (or depths, in the case of zooplankton) that allows them to maximize energy gain via feeding (such as on algae) while minimizing the probability of death via predators (such as fish). To test this intuitively appealing theory, we designed two experiments. The first test was based in a marine lagoon in 1994 on San Juan Island, Washington, where large (3-cubic-meter) plastic enclosures contained the marine copepod *Acartia hudsonica*. More recently we worked with the freshwater cladoceran *Daphnia hyalina* in the 11-meter-tall "Plankton Towers" at the Max Planck Institute in Germany. US funding for this work was provided by the National Science Foundation and the Office of Naval Research. In both systems the abundances of algae and predatory fish—which could be quantitatively related to feeding gains and the probability of predation mortality, respectively—were manipulated in the experimental containers.







Jack Cook

Zooplankton in experimental chambers exhibit diel vertical migration in the presence of visual predators such as fish to avoid being eaten during the day (A), but remain in the surface day and night to feed on algae (green dots) when fish are absent (B). Moreover, zooplankton can make subtle trade-offs between the risk of predation and the benefit of feeding when both food and predators are present, such as occurs in nature—zooplankton migrate under conditions of low food and high fish abundance (C), but are non-migratory under conditions of high food and low fish abundance (D)

Both types of zooplankton behaved largely as the theory predicted. Manipulations of either fish or algae alone triggered migratory and nonmigratory behavior, respectively. That is, in the presence of fish, zooplankton entered food-rich surface waters only under cover of darkness, when risk from visual predators such as fish was low. However, in the presence of abundant food but no fish, zooplankton remained in the surface layer day and night. A more interesting result emerged in the subtle interactions between fish and algae when both were manipulated simultaneously: Diel vertical migration was triggered only under precise conditions of high fish and low food abundance, whereas slightly lower fish abundance and slightly higher food abundance resulted in nonmigratory behavior. In short, individual zooplankters seemed to choose to reside in particular depths at particular times of day and night based on subtle trade-offs between gains from feeding on algae and the risk of being eaten by fish.

There is much more to be learned about different behaviors of aquatic animals, including diel vertical migration, and collaborations between experimentalists and theoreticians that cut across marine, freshwater, and even terrestrial systems may prove to be a particularly effective approach.

An AB(L)E Bodied Vehicle Proves Its Worth

Dana R. Yoerger
Associate Scientist, Applied Ocean Physics & Engineering Dept.
Albert M. Bradley,
Senior Engineer, Applied Ocean Physics & Engineering Dept.
Barrie B. Walden
Principal Engineer, Applied Ocean Physics & Engineering Dept., and Manager, Submersible Engineering & Operations

The Autonomous Benthic Explorer (*ABE*) can survey the seafloor to depths of over 5,000 meters. Designed to complement WHOI's existing vehicles such as *Alvin* and *Jason*, *ABE* operates without a tether or human supervision. As its capability evolves, we plan to use *ABE* to observe time-varying phenomena lasting from days to months, particularly in active hydrothermal vent areas. (See *Oceanus* Spring/Summer 1995 for a more complete description of ABE's National Science Foundation-funded development and its capabilities).


Dawn Wright

Scientists and crew launch *ABE* from *Atlantis II* during the vehicle's first science dives in the summer of 1995.

During the summer of 1995, ABE successfully completed its first set of science dives on the Juan de Fuca Ridge at depths to 2,400 meters. We proved many of *ABE*'s features from an engineering perspective and *ABE* made maps of seafloor magnetic anomalies (see article opposite), took video snapshot images of the new lava terrain, and mapped the conductivity and temperature of an active hydrothermal vent. *ABE* operated from *Atlantis II* (*AII*), utilizing the nighttime periods between *Alvin* dives.

Each dive began with a controlled descent to a specified spot on the seafloor. Navigating by the same acoustic transponders *Alvin* uses, *ABE* took about two hours to reach the seafloor. While we couldn't exercise any control over *ABE*, we could observe its movements from the ship through the transponder navigation system. *ABE* sent out a coded acoustic signal to indicate when it had successfully reached the bottom and again when it had released its descent weight and started its mapping run.

To map the lava terrain, *ABE* executed a sequence of tracks, each at constant heading and constant forward speed. The vehicle could run at constant depth, or it could follow the bottom using a single beam fathometer and a control algorithm to ascend, descend, or slow down to maintain a preset height off the rugged seafloor. At the end of the prescribed set of tracklines (lasting up to three hours), *ABE* dropped its ascent weights and headed for the surface. Guided by the acoustic tracking, we directed *AII* to follow *ABE* until it surfaced shortly before dawn. On the surface, flashing strobes made *ABE* easy to spot, even in rough seas. We recovered ABE at first light, then read the data files, charged the batteries, and reloaded descent and ascent weights for the next deployment. After scrutinizing *ABE*'s performance, we planned the next run, reprogrammed *ABE*'s control computer, and tested the new mission software in simulation.

ABE's final dive of the series was perhaps the most exciting. We directed *ABE* to the edge of a hydrothermal plume previously discovered using *Alvin*. *ABE* executed an expanded survey pattern while negotiating the most rugged terrain it had experienced. After the dive, *ABE*'s temperature and bathymetry data revealed a large diffuse plume centered over a graben, or shallow valley. The vehicle's video showed the lava terrain as well as the hydrothermal plume.

ABE's first science mission produced detailed maps of the seafloor, and also taught us much about the performance of the vehicle, which made over 35 kilometers of bottom tracks during seven dives. We obtained detailed records of *ABE*'s power consumption, performance of its navigation and control systems, and its sensor systems. Based on this success, we plan to extend *ABE*'s endurance in order to capture long-term, dynamic events.

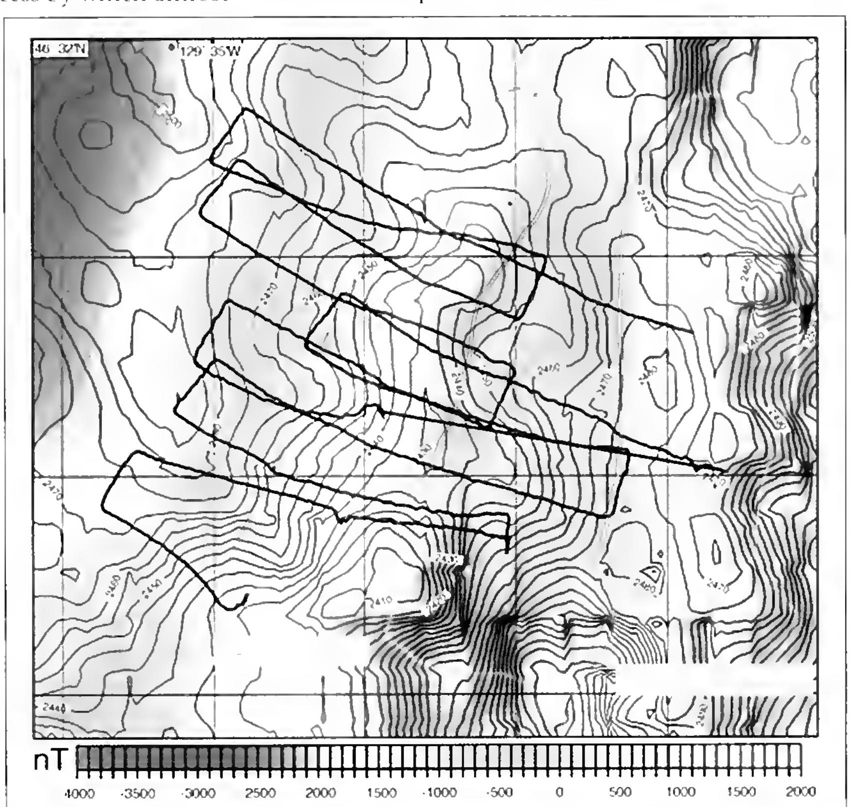
From the Beginning: Monitoring Change in a Young Lava Flow

Maurice A. Tivey
Associate Scientist, Geology & Geophysics Department

A unique opportunity to monitor changes in a seafloor lava flow nearly from its inception began in the summer of 1993. Just days after National Oceanic and Atmospheric Administration scientists activated a new real-time earthquake monitoring network, seismic activity was detected on the Juan de Fuca ridge in the northeast Pacific. This activity indicated that an eruption was underway, and research vessels were dispatched to locate it. The eruption, which formed a lava flow 30 meters thick, 1,500 meters long, and 300 meters wide, was fed from what is thought to be a subsurface feeder dike (a fissure that serves as a conduit from a body of molten material to the seafloor). Using conductivity-temperature-depth instruments, scientists aboard research ships were able to detect hot water plumes from vents created by the cooling lava as it heated the seawater. Echosounding ships repeating previous mapping tracks also recorded a difference in the depth of the seafloor where the lava flow had erupted. Together the diking event and lava flow represent the basic building block of oceanic crust—by investigating this newly emplaced seafloor feature we can better understand the process by which almost 70 percent of Earth's surface has formed.

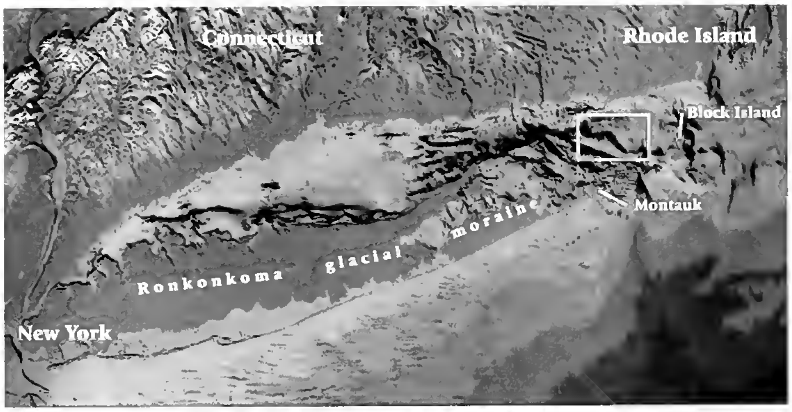
The physical properties of the new lava are still pristine, and knowing the precise age of the rocks allows us to monitor their changes over time. One important property is magnetism and new lava turns out to be highly magnetic. As the molten lava is rapidly "quenched" or cooled on contact with seawater, the magnetic minerals it contains quickly "freeze," recording the direction and strength of Earth's magnetic field, which varies over time. The feeder dike, however, lies beneath the seafloor and cools more slowly, so its magnetism is much weaker. This difference in magnetic properties can be used to map the extent of the dike zone beneath the new flow and helps us to understand the sources and placement of lava. In summer 1995, Paul Johnson (University of Washington) and I led a National Science Foundation-funded *Alvin* submersible cruise to map the magnetic and gravity fields of the new flow and dike and to establish a benchmark set of measurements for future surveys. As part of the nighttime survey plan, the WHOI-developed autonomous underwater vehicle *ABE* carried out its first science mission. Complementing *Alvin*'s close-up views of the seafloor obtained during daytime submersible operations, *ABE* mapped the magnetic field over the new lava flow and dike zone. The vehicle successfully carried out over 35 kilometers of tracklines, measuring not only the magnetic field but also the bathymetry, and taking digital photographs of the seafloor lavas. This relatively simple exercise belies the technological expertise that allows *ABE* to operate reliably in the deep ocean (see the article opposite). Building on this successful pioneering effort, autonomous vehicles like *ABE* hold promise for long-term remote monitoring as we continue to explore the seafloor.

An image of fresh lava in the study area was captured by the Canadian remotely operated vehicle *Ropos*.



Maurice Tivey

The figure at left shows *ABE*'s data collection track (black lines running left and right) over the new lava flow superimposed on a magnetic map of the area.



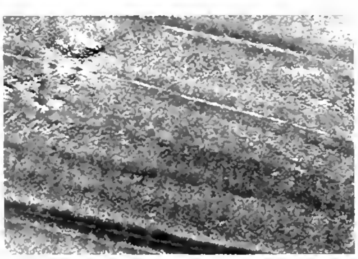
White rectangle shows Block Island Sound area surveyed in 1991 and 1994. Lighter shades of green denote regions with higher elevations above sea level and darker shades of blue indicate regions with greater water depth

Scientists Study Large Storm and Human Effects in Block Island Sound

Neal Driscoll
Assistant Scientist, Geology & Geophysics Department

When Nor'easters, hurricanes, and other large storms pummel the US East Coast, resulting property damage ashore is highly visible. However, knowledge of how large storms affect the shallow water regions of the continental shelf remains limited, at best. Increased societal pressure on these environments indicates a need for better understanding of fundamental physical processes that shape them. By determining the natural variability of shallow water regions, society can assess the interplay of anthropogenic and natural effects on these regions and develop strategies for responsible management of their resources.

Toward this goal, the author and Dave Twichell (US Geological Survey) led an Office of Naval Research-sponsored expedition to survey portions of Block Island Sound before and after large storms. Recent improvements in navigation, afforded by the differential Global Positioning Satellite System (GPS), allowed us, aboard R/V *Cape Henlopen* (University of Delaware), to reoccupy in 1994 an area in Block Island Sound where similar geophysical and geological data were acquired in 1991. Our objective was to establish a "natural laboratory" where repeated surveys could monitor how the seafloor and its sediments change with time. These data then can be used to describe the influences of hurricanes, large storm events, and anthropogenic activity on the distribution and type of bedforms, sediment composition, and the acoustic character of shallow water sediments. We collected sonar images of the seafloor both in cross section and in map view, recovered surface sediments from the seafloor, and recorded seafloor roughness and megafauna with an underwater camera sled. Combination of these data sets allows characterization of the geologic features in and around Block Island Sound both before and after the passage of large storm systems. We also examined the region's benthic biology to assess how biological activity might affect seafloor erodibility.



The boulders in the upper left corners of these photos were used to coregister the 1991 (top) and 1994 images for comparison purposes. Note that the trawl marks visible in 1994 do not appear in the 1991 image.

Analysis of the Block Island Sound data indicates that large storm systems have had little effect on large-scale morphology and sedimentary bedforms. One explanation for this surprising observation is that the submerged portion of the Ronkonkoma glacial moraine that extends from the eastern tip of Long Island to Block Island and continues northward toward Point Judith, Rhode Island, acts as a natural jetty at the mouth of Block Island Sound, dissipating much of the storms' wave energy. The shallowest portions of the submerged moraine are 8 to 10 meters deep, whereas the study area is shoreward of this shoal in 30 to 50 meter water depths. Much of Block Island Sound is in the lee of both the subaerial and submerged portions of the glacial moraine and thus protected from large, storm-induced waves. Consequently, the glacial morphology imparted by the Laurentide ice sheets almost 18,000 years ago still influences present-day sediment transport, erosion, and deposition in Block Island Sound.

However, on a smaller scale (meters), some portions of the study area have undergone dramatic changes. One obvious change in the 1994 data set compared to the 1991 survey is the increase in the distribution and density of trawl door scars caused by fishing gear dragged across the seafloor. This suggests that anthropogenic effects are having a grater impact on reworking surface sediments in Block Island Sound than large storms. A long-term research goal is to develop additional natural laboratories in a variety of shallow water settings to examine the relative effects of storms, anthropogenic activities, and other processes on different portions of the continental shelf. Increased knowledge about the processes that shape and sculpt the present-day continental shelf will yield important insights into both interpreting the geologic record and responsible management of an invaluable resource.

Exploring Volcanoes, Earthquakes, and Mountain Building Under the Atlantic Ocean

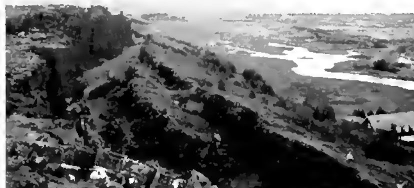
Jian Lin
Associate Scientist, Geology & Geophysics Department

Each year hundreds of thousands of earthquakes shake the ocean floor along the Mid-Atlantic Ridge. Only the largest of these quakes are detectable by seismic stations on land, but they are part of a continuous mountain building process along the 50,000-kilometer-long mid-ocean rift that circles the globe. In the past several years, my colleagues and I have been using a variety of acoustic sonars and marine geophysical sensors to explore underwater volcanoes and earthquakes, aiming at a better understanding of the submarine mountain building process that has shaped more than 70 percent of Earth's solid surface.

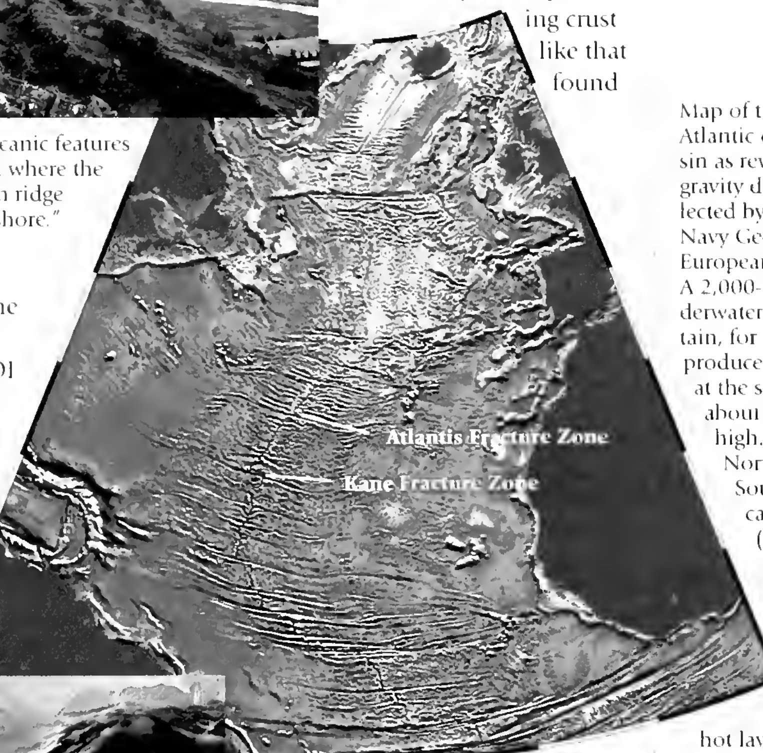
In July 1995, the US Navy declassified precision gravity data collected by the Navy Geosat satellite from 1985 to 1990. This newly available information on the world's ocean basins is 30 times more detailed than data previously available. Geosat's radar recorded the precise shape of the ocean surface, which reflects the contours of underwater mountains and valleys. MIT/WHOI Joint Program students Javier Escartin and Garrett Ito and I have analyzed some of the newly released data for the Atlantic to study the geology of many fascinating submarine features. These include "fracture zones," which are deep valleys produced by seafloor earthquakes, and submarine "hot spots," where an unusually large amount of molten lava has oozed onto the seabed near such prominent islands as Easter, Iceland, and the Galapagos.

While Geosat's 2-to-10-kilometer resolution provides a good overview, finer resolution of seafloor features relies on the use of surface ships equipped with the latest marine technologies. With support from the National Science Foundation and the Office of Naval Research, we have focused especially on a 1,000-kilometer-long stretch of the Mid-Atlantic Ridge between the Kane and Atlantis fracture zones and a 250-by-400-kilometer area of 0-to-30-million-year-old crust. We have employed a variety of acoustic sonars and geophysical sensors to measure the precise shape of the seabed, sediment thickness, and the magnetic and gravity properties of Mid-Ocean Ridge rocks.

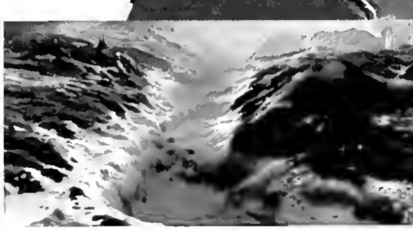
Among the most surprising results is the finding that the seemingly continuous mountain range under the Atlantic Ocean is in fact composed of many individual spreading cells or segments. The lengths of many 20-to-100-kilometer-long spreading segments have changed surprisingly fast, at a rate close to that of seafloor spreading itself (about 1 centimeter, 0.4 inch, per year). These results suggest that, unlike the two-dimensional, crust-producing machine depicted in many geology textbooks published in the 1960s and 1970s, the mountain building process along the ocean ridges is highly punctuated in space and time, especially in relatively slow-spreading crust like that found in the Atlantic basin.



Rifted volcanic features in Iceland where the mid-ocean ridge "comes ashore."



Map of the North Atlantic ocean basin as revealed by gravity data collected by the US Navy Geosat and European satellites. A 2,000-meter underwater mountain, for example, produces a bump at the sea surface about 2 meters high. As the North and South American plates (left) pull away from the European and African plates (right), hot lava oozes up to form the Mid-Atlantic Ridge (orange/red in the center). Lines perpendicular to the ridge are fracture zones where plates pass each other, offsetting the ridge and producing earthquakes.
Map produced by Javier Escartin, MIT-WHOI, with data from David Sandwell, Scripps Institution of Oceanography and Walter Smith, NOAA



Computer-generated image shows view from the Mid-Atlantic Ridge rift valley looking into the Atlantis Fracture Zone.

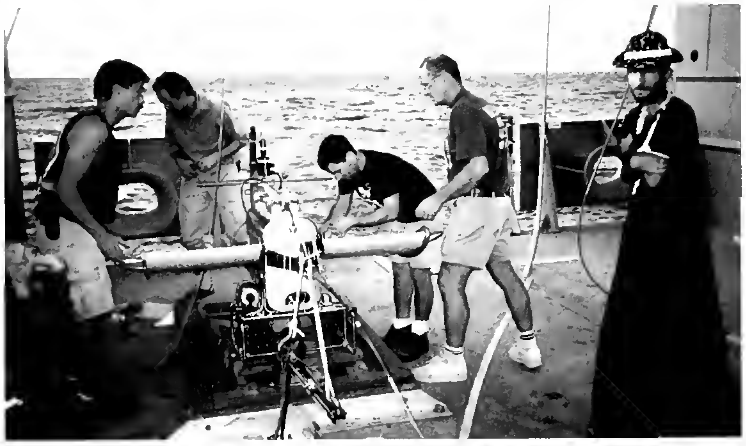
With support from the National Science Foundation's RIDGE (Ridge Inter-Disciplinary Global Experiments) program, we are mounting two major expeditions in summer 1996 to directly image the internal structure of volcanoes and mountain ranges under the Atlantic Ocean using seismic waves from artificial sources and natural earthquakes. We believe there is still much to be learned about the underwater volcanoes, earthquakes, and mountain ranges that shape two-thirds of our planet.

Changing Winds and Ocean Mixing: Studies of the Arabian Sea Monsoon

Kenneth H. Brink
Senior Scientist, Physical Oceanography Department
Frank Bahr
Research Associate, Physical Oceanography Department

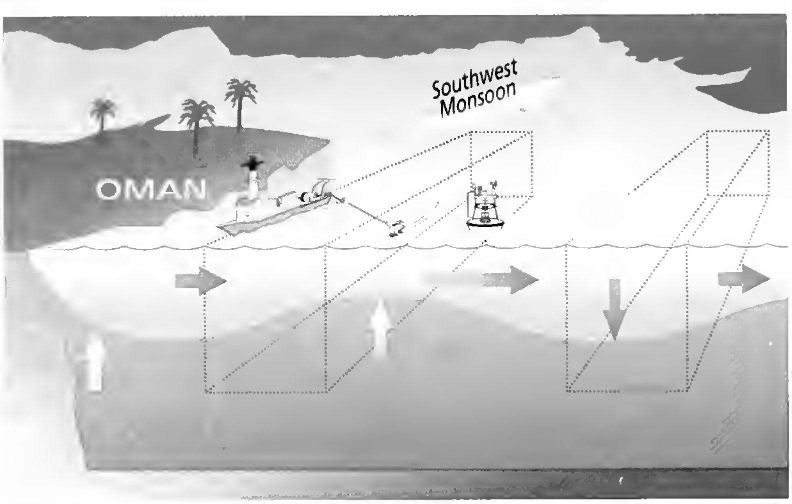
The Arabian Sea, located between the Arabian penninsula and the Indian subcontinent, is unique among the world's ocean basins because its basin-scale winds reverse completely during the course of the year in a phenomenon known as a monsoon. While this happens locally along some coastlines (such as off Oregon), it is indeed unusual to have it happen on so large a scale. The implications of these reversals are considerable as they imply a tendency for the whole circulation to switch directions each year. Imagine, by analogy, the Gulf Stream changing direction each summer! The winds driving the currents are even more interesting: Hot summertime winds blowing in a concentrated jet off desert Africa towards India constitute the strongest sustained winds to be found anywhere over the ocean except near Antarctica, where the ocean's structure is quite different.

One of the basic concepts in physical oceanography is that when a wind blows on the ocean surface, the earth's rotation causes the turbulent flow in the upper 50 meters of the water column to move to the right of the wind in the northern hemisphere. The implications of this well-demonstrated idea are shown in the figure below left. When winds are strong, such as under the Arabian Sea jet, then upper ocean currents flow strongly to the right. When winds are weaker, there is still a transverse flow, but it is less intense. This implies that some water moves upward on the left of the jet and downward on the right of the jet in order to make up the differences. The result is that cold, deep, nutrient-rich water comes to the surface close to shore and to the left of the jet. We wanted to understand the strength of this upwelling response and how it affects ocean mixing.



From left, Craig Lee, Frank Bahr, Paul Fucile, and Jerry Dean prepare SeaSoar for deployment while Omani observer Rashid Al-Fahihi looks on.

Ken Brink



Schematic of winds and circulation in the Arabian Sea during the summer. The boxes denote the portions of the ocean WHOI physical oceanographers sampled most closely.

Jayne Doucette

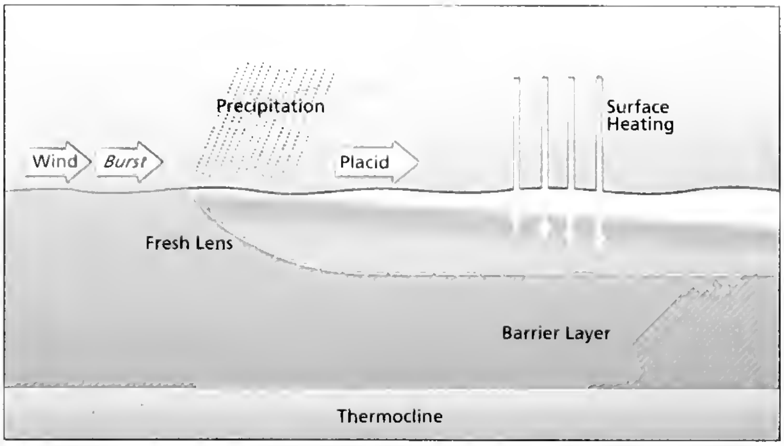
The wind cycle over the Arabian Sea presents a challenge to US oceanographers. Though this is obviously an interesting region to study, the geographical distance from our home base and the difficult weather conditions have severely limited prior studies. Nonetheless, the WHOI SeaSoar group set out to do four 1994–1995 cruises in the Arabian Sea to observe the consequences of the monsoon wind cycle. Our work was tied to a broader program sponsored by the Office of Naval Research, which funded our work, and the National Science Foundation. We used the towed, undulating sampler SeaSoar to measure temperature, salinity, and other variables in boxes on either side of the main summertime jet. While we are still processing the measurements, the cruises, based in Oman, were an adventure, and preliminary results show promise of some striking new insights on upper ocean circulation in this area. For example, we have found stong analogies with summertime flow patterns off the coast of California.

New Findings On The Western Equatorial Pacific's Warm Pool

Steven P. Anderson
Assistant Scientist, Physical Oceanography Department
Robert A. Weller
Senior Scientist, Physical Oceanography Department

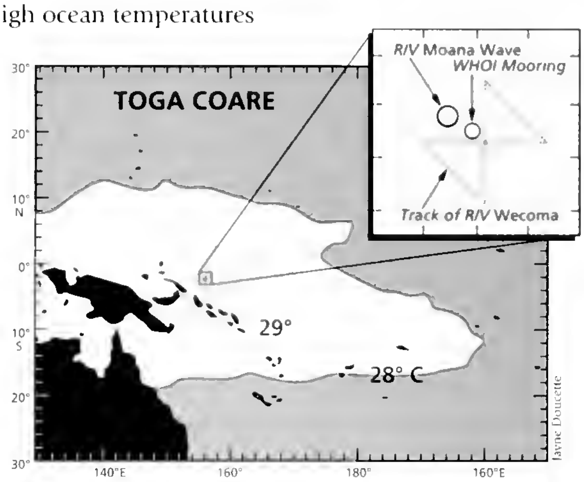
The warmest open ocean waters in the world are found in the western equatorial Pacific. In an area the size of Australia, annual average upper ocean temperatures exceed 29° C. This warm pool is closely associated with a combination of intense upward transport in the atmosphere, cloud cover, and rainfall that constitutes a major driving force for global atmospheric circulation. Eastward displacement of this warm pool system during El Niño/Southern Oscillation (ENSO) events every 3 to 5 years results in pronounced midlatitude weather pattern changes. Understanding the processes that couple the ocean and atmosphere in the warm pool is a crucial step toward improving predictions of seasonal-to-interannual global climate variability. Pursuit of this understanding is the primary objective of the Tropical Oceans/Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE).

What maintains the high ocean temperatures found in the warm pool? After all, other regions of the ocean have less cloud cover, and thus more solar heating, yet do not get as warm as the western equatorial Pacific. One hypothesis ascribes an important role to the large amount of precipitation—greater than 4 meters per year—that falls in the warm pool region. This rain forms a shallow, fresh—and thus buoyant—layer on the ocean surface that supports the accumulation of heat. A salt-stratified or "barrier" layer beneath it effectively insulates surface waters from cooler waters found at depth. The barrier layer is maintained over the long term through freshening of the near-surface, warm pool by rainfall that is balanced by sporadic mixing with saltier waters transported by the South Equatorial Current from the central tropical and subtropical Pacific.



Schematic diagram illustrates the "barrier layer" theory. During a strong wind burst, the surface mixed layer extends down to the top of the thermocline (region of rapid temperature decline). Following the wind burst, the additional buoyancy from precipitation and strong surface heating results in a relatively warm and fresh, thin surface mixed layer. Below this thin layer is a strong salt-stratified or barrier layer, which effectively decouples the surface forcing from the deeper water.

As part of COARE, a multi-national group of scientists using several research vessels mounted an intensive field observation program in the warm pool from October 1992 through March 1993. The data collected is being used to study the basic processes that link the atmosphere to the ocean in the region. A central part of this observational program was a discus buoy moored in the middle of the warm pool by the WHOI Upper Ocean Processes group led by the authors and Albert Plueddemann. The mooring instrumentation included a complete meteorological set on the buoy to observe the local atmosphere, and oceanographic sensors on the mooring line to monitor the salinity, temperature, and currents in the upper ocean.



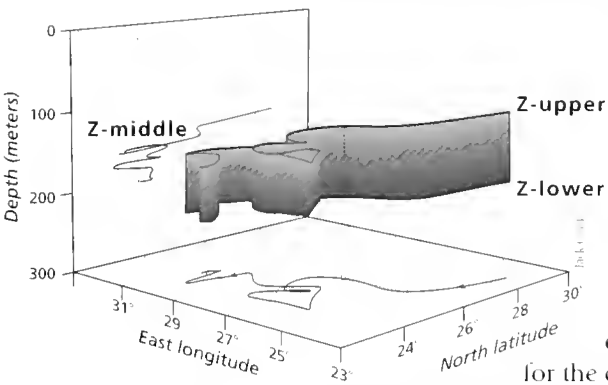
Cruise tracks and mooring location are shown for Tropical Ocean/Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) research on the western equatorial warm pool. Annual mean sea surface temperature was calculated by the National Oceanic and Atmospheric Administration National Meteorological Center Climate Analysis Center. *Moana Wave* is operated by the University of Hawai and R/V *Wecoma* by the University of Washington.

We are analyzing the response of the warm pool surface layer to local surface forcing using the mooring observations made during COARE. To test the barrier-layer hypothesis, we are using numerical ocean models to examine local rainfall's role in determining the vertical structure of the near-surface waters of the warm pool and its net effect on sea surface temperature. Our findings support the salt-barrier-layer theory. We are now working with climatologists to improve the warm pool surface layer's mathematic representation in the global, coupled atmosphere-ocean models currently used for long term climate prediction.

Bobber Floats Measure Currents' Vertical Component in the Subduction Experiment

James F. Price
Senior Scientist, Physical Oceanography Department

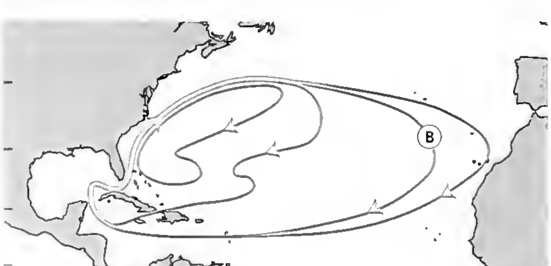
Generally we think of the open ocean as very deep and cold, and, indeed, it is in most respects. However, if we were to observe an entire ocean basin from a distant vantage point, say the moon, then our impression would be that the oceans are not so deep but are actually very thin—for example, the North Atlantic is only about 4 kilometers deep while it is about 4,000 kilometers wide. The size and shape of some of the most important ocean currents, such as those associated with the subtropical gyre (figure below), are constrained in large part by this aspect ratio, which thus has a major consequence for the character of ocean currents. In particular, the vertical component of large-scale ocean currents is necessarily very much smaller than their horizontal component. Thus when we say "currents" in the context of observations, it is usually understood that we mean the horizontal component only.



The three-dimensional trajectory of a Bobber float launched in the eastern subtropical gyre of the North Atlantic. This trajectory is about 1,000 kilometers in length and two years in duration. Notice that the Bobber descends about 80 meters

The vertical component of ocean currents, though small, has an importance for ocean dynamics that is in some crucial respects equal to that of the much larger horizontal component. Because vertical measurements are more difficult to make, oceanographers have only recently begun to develop measurement techniques for them. During the 1991 to 1993 Office of Naval Research-funded Subduction Experiment, designed to examine the descent of near surface water as it moves south in the eastern portion of the subtropical gyre, we tried an approach that appears to provide a first look at the three-dimensional currents in the subtropical gyre. The idea was to track a new and clever float, called a Bobber, that was developed and constructed by Doug Webb of Webb Research Corporation (Falmouth, Massachusetts). Bobbers drift freely with the horizontal currents at their depths, similar to conventional subsurface floats. Bobbers are among the first of a new generation of subsurface floats that can vary their buoyancy under programmed control. Bobbers may be programmed to move up and down once each day between upper and lower isotherms—19° C and 17.5° C in the case of Bobber 15 shown in the upper left figure. The depths at which the Bobber found these isotherms, Z-upper and Z-lower, was encoded into an acoustic signal and telemetered daily to give the slowly varying, vertical component of the trajectory. During a two-year lifespan, Bobber 15 moved southward from about 29° N to about 23° N, and at the same time it descended, following the target isotherms, from a mid-depth (Z-middle) of 125 meters down to about 200 meters. The downward displacement is quantitatively consistent with the expected downward "Ekman pumping" that results from the anticyclonic wind stress curl of the overlying Azores high pressure system. Note that the thickness of the current defined by the target isotherms decreased from about Z-lower – Z-upper = 80 meters, when the Bobber was farthest north, to about 50 meters when it was farthest south. This decrease in current thickness is qualitatively consistent with the convergence of the vertical velocity expected in the wind-driven subtropical gyre. Indeed the decrease in current thickness is a little more than expected, perhaps indicating an effect of vertical mixing in the heat balance.

Researchers prepare to launch a Bobber (long cylinder) from R/V *Oceanus* during the Subduction Experiment.



A simplified rendition of the subtropical gyre or flow pattern. The letter "B" indicates the location of the Bobber deployment.

Improving Weather Forecasts with Better Marine Measurements

James B. Edson
Associate Scientist, Applied Ocean Physics & Engineering Dept.

Numerical weather forecasts have markedly improved over the past several decades. Unfortunately, there are still times when the model predictions lead to inaccurate forecasts. Ongoing improvements to these models and their forecasts involve three major areas of research:

- development of faster computers that would allow modelers to include more physics and higher resolution,
- planning for a better and denser network of surface and upper air observations to initialize these models, and
- improvements to the way we include processes that even high-resolution models cannot resolve.

With or without better computers, accurate prediction of weather over the sea would greatly benefit from any improvements in the last two categories. Weather observations over the world's oceans are sparse, and modelers must work with little or no information from vast regions of the ocean as they initialize forecast models. In addition, the fluid ocean surface presents unique challenges to marine researchers attempting to describe ocean/atmosphere coupling.

Along with a team of US and European researchers, I am actively involved on both of these research fronts. We are improving the way we estimate surface winds over the open ocean from satellites. For example, radars can be used to infer wind speed and direction by bouncing (scattering) microwaves off the ocean surface. Basically, the method relies on the observation that, in general, the higher the wind speed the rougher the ocean surface, and the rougher the ocean surface the larger the returned (backscattered)

(Continued on next page)

FLIP Provides a Stable Research Platform

Erik Bock and Jim Edson worked aboard *FLIP* (Floating Instrument Platform) on two different research projects in 1995. The 355-foot (108-meter) *FLIP*, operated by the Scripps Institution of Oceanography, is ingeniously designed with hinged equipment that can be used with the vessel in either its horizontal or vertical position. *FLIP* is towed to a research site where ballast tanks are flooded with 1,500 tons of seawater to "flip" it to the vertical position (while scientists and crew literally "walk up the walls" to stay upright). With only 55 feet (17 meters) of the vessel above the surface and the remaining 300 feet (91 meters) extending into the stable water column, scientists can pursue their measurements almost unaffected by surface motion. This allows many scientific measurements that would be difficult or impossible to make from a conventional research vessel. At the end of the experiment, which may last up to the 35 days, compressed air is blown into the ballast tanks, and the vessel returns to its horizontal position.

Carl Friehe, UC Irvine

Jim Edson examines a 50-foot mast deployed off *FLIP*'s port boom for his spring 1995 work in the Pacific with Carl Friehe and Scott Miller (University of California, Irvine). Along with colleagues from Scripps and New Zealand they are using their measurements to investigate ocean/atmosphere coupling.

(Continued from previous page)
signal. By refining this simple concept, we can improve the accuracy of these observations and widen their application.

Over the past three years, we have investigated how ocean waves influence the behavior of near-surface atmospheric turbulence. In the spring of 1995 Carl Friehe and Scott Miller (University of California, Irvine) and I spent a month off the Monterey coast aboard the research platform *FLIP* as part of Office of Naval Research Marine Boundary Layers program.

Once "flipped," we assembled a heavily instrumented 50-foot mast for deployment off *FLIP*'s port boom. Our objective was to measure the wind profile and the transport of energy and momentum to and from the ocean surface. Additional measurements made aboard *FLIP* included radar images of the sea surface by researchers from the University of Massachusetts and New Zealand's National Institute of Water and Atmospheric Research, Ltd., and upper ocean measurements by the Scripps scientists. We are currently combining all the *FLIP* measurements in order to describe the coupling of the atmospheric and oceanic boundary layers.

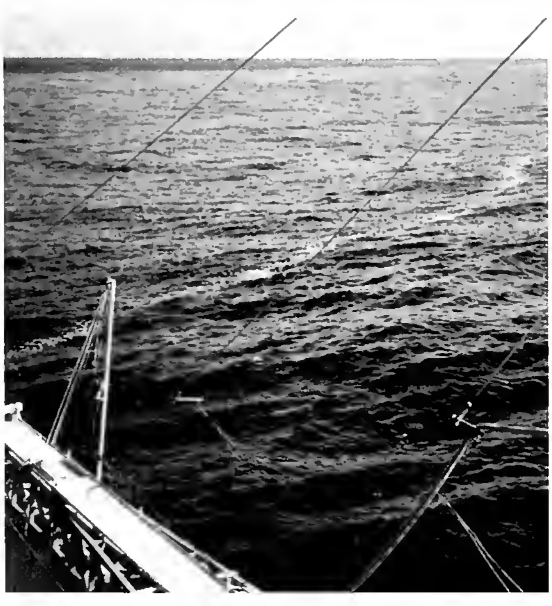
Experiment Compares Direct and Radar Measurements of Internal Waves

Erik J. Bock
Associate Scientist, Applied Ocean Physics & Engineering Dept

The Coastal Ocean Process Experiment (COPE) employed *FLIP* off the Oregon coast, near the towns of Garibaldi and Tillamook, in August and September 1995 to learn how radars image internal waves. The experiment was sponsored by the Department of Defense and conducted by the Environmental Technology Laboratory located in Boulder, Colorado. Internal waves propagate beneath the sea surface at the depth where there is a difference in density between lighter surface water and the heavier deep waters. The density difference is caused by temperature or salt concentration differences, or a combination of these. Resulting internal waves can produce current surges that cause the short surface waves to "bunch up" and become unusually rough. This roughness can be measured both directly and by radars.

For the direct measurements from *FLIP*, we used a special WHOI-designed, 16-foot research catamaran, equipped with an instrument that directly measures the short waves that are affected by internal waves. The catamaran was moored between *FLIP* and a separate, anchored yellow-foam buoy. A multi-week experiment allowed a comparison between direct measurements of waves at the *FLIP* site and remote measurements by radars mounted on top of Onion Hill 14 miles away on the Oregon coast. The figures show the passage of an internal wave as photographed from *FLIP*. The two images, taken a few minutes apart, show that the internal wave (evidenced by the brighter band of short, breaking waves extending off in the distance) traveled an appreciable distance in the time elapsed between the two photographs. Radar measurements, because they have greater spatial coverage, can be useful in relating observations that span kilometer scales to ocean properties like bathymetry. Results from the radar experiment are not yet available.

Two photos taken a few minutes apart from *FLIP* show the surface effect of an internal (subsurface) wave.



Chris Zappa, APL, UW

Radionuclide Studies Indicate an Historically Hardy "Conveyor Belt"

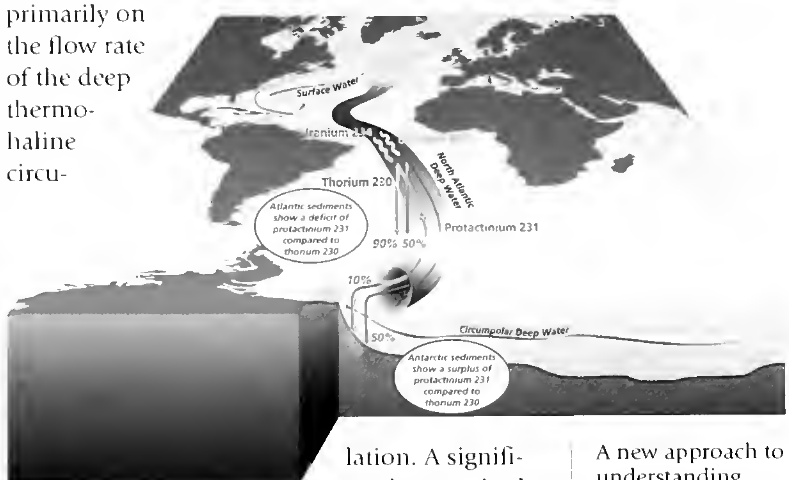
Roger François
Assoc. Scientist, Marine Chemistry & Geochemistry Dept
Ein-Fen Yu
Guest Investigator, Marine Chemistry & Geochemistry Dept
Michael Bacon
Chairman and Senior Scientist,
Marine Chemistry & Geochemistry Department

The broad features of modern deep ocean circulation are often described as a thermohaline "conveyor belt" initiated by the formation of North Atlantic Deep Water (NADW) as it sinks in the Norwegian, Greenland, and Labrador Seas and flows southward into the Circumpolar Deep Water (CPDW) around Antarctica. This general pattern of circulation affects global climate as it drives warm, low-latitude surface waters to the north to replace the sinking water. It also influences the sequestering of carbon dioxide into deep water, thereby regulating the carbon dioxide concentration of the atmosphere and the "greenhouse" effect on the earth's heat balance.

Changes in deep water circulation may have played an important role in controlling global climate during the geological past, especially during the last million years, a period characterized by cyclical climatic oscillations between ice ages and warm interglacial periods. Variations in the isotopic and chemical composition of calcite shells of foraminifera living on the seafloor document significant changes in deep water circulation during the last ice age, when NADW was replaced by the Glacial North Atlantic Deep/Intermediate Water (GNAIW) flowing at shallower depth. However, the shells do not provide information on the rate at which this glacial water mass was produced or whether it even reached the Antarctic Ocean and mixed with CPDW.

In an effort to evaluate past changes in the rate of "conveyor belt" circulation and document whether GNAIW reached the CPDW, we are taking a new approach based on the partitioning of two radionuclides, protactinium 231 (^{231}Pa) and thorium 230 (^{230}Th). These two long-lived radionuclides (half-lives: 32,000 years and 75,000 years) are the decay products of two natural isotopes of uranium dissolved in seawater. Both are "particle-reactive," that is, they are rapidly removed to the seafloor by adsorption onto sinking particles. ^{230}Th, with a very strong affinity for particles, resides in the water column for only a few decades, while the somewhat less particle reactive ^{231}Pa resides in seawater for more than a century. In the modern ocean, deep water resides on average 200 years in the Atlantic before being exported into the CPDW. Because its mean residence time in seawater is 10 times shorter, 90 percent of the ^{230}Th produced in Atlantic water is removed to the underlying Atlantic sediments. In contrast, with a residence time similar to that of deep water in the Atlantic, only 50 percent of the ^{231}Pa produced is removed to Atlantic sediments. The remainder is exported with NADW into the CPDW for eventual deposit in the sediments of the Antarctic Ocean. Consequently, there is a deficit of ^{231}Pa compared to ^{230}Th in Atlantic sediments, and a surplus in sediments of the Antarctic ocean.

The contrast between the two oceans depends primarily on the flow rate of the deep thermohaline circulation. A significant decrease in the rate would result in a lesser ^{231}Pa deficit in Atlantic sediments, while a surplus of ^{231}Pa in Antarctic sediments would indicate addition of deep Atlantic water into CPDW. We measured ^{231}Pa and ^{230}Th in Atlantic and Antarctic sediments deposited during the last glacial maximum and compared it with the postglacial values. After correction for radioactive decay, we found very little difference between the two time intervals, indicating that GNAIW reached CPDW and there was essentially no change in the rate of the global "conveyor belt" circulation. This important information bears on our understanding of the influence of deep water circulation on the global climate and atmospheric carbon dioxide level during the last ice age.



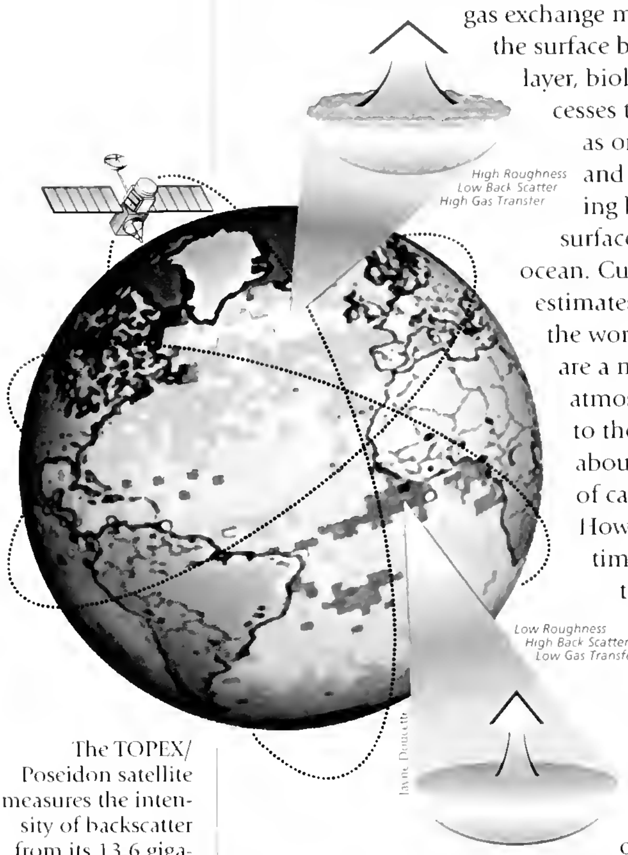
Jack Cook

A new approach to understanding how changes in deep water circulation may influence global climate is based on examination of the amounts of the radionuclides protactinium 231 and thorium 230 deposited in Atlantic and Antarctic sediments as deep water travels along the "conveyor belt" path.

Estimating Air-Sea Gas Exchange with a New Satellite Data Method

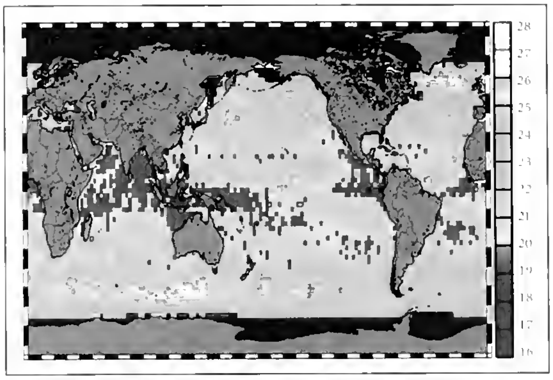
Nelson M. Frew
Senior Research Specialist,
Marine Chemistry & Geochemistry Department

Increasing concern about the accumulation of greenhouse gases such as carbon dioxide (CO_2) in the troposphere and its potential impact on climatic change challenges oceanographers to better understand ocean-atmosphere interactions. The oceans play a significant role in removing and sequestering the CO_2 added to the atmosphere by human activities. The removal process is controlled by several factors, including physical gas exchange mechanisms in the surface boundary layer, biological processes that fix CO_2 as organic matter, and vertical mixing between the surface and deep ocean. Current flux estimates suggest that the world's oceans are a net sink for atmospheric CO_2, to the tune of about 2 gigatons of carbon per year. However, the timing and spatial distribution of this uptake are very poorly known, and there is an inherent uncertainty of a factor of two in the models used to estimate gas exchange rates, which currently are based on ocean wind speeds. Gas exchange is a wind-driven process because it is the wind that produces waves and the associated turbulence that promotes equilibration of the gas between the atmosphere and the sea. However, other factors, such as variable fetch, atmospheric stability, and the presence of organic films on the sea surface, can modulate the wind's stirring effect and complicate estimates of gas transfer rates.



The TOPEX/Poseidon satellite measures the intensity of backscatter from its 13.6 gigahertz radar beam. Here the beam illuminates two regions of the sea surface, one smooth, one wind-roughened. Yellow arrows represent air-sea gas transfer rates. The magnitude and direction of the carbon dioxide flux (into or out of the ocean) depends on the local air-sea carbon dioxide concentration gradient.

David Glover and I are exploring a new method for estimating gas transfer independent of wind speed. Our project, part of an Earth Observing System (EOS) Interdisciplinary Science Investigation sponsored by the National Aeronautics and Space Administration, focuses on applying satellite-derived information to studies of chemical and biological processes in the surface ocean. The new approach uses the data stream from the TOPEX/Poseidon satellite altimeters, which illuminate a 10-kilometer-wide swath of the earth's surface along the flight path with pulsed microwave radar at a frequency of 13.6 gigahertz. While the primary use of the altimeter is to measure sea surface heights using the travel time of the reflected radar pulse, information about sea surface roughness can be obtained from the intensity of the return signal. During low wind periods, when the sea surface is relatively smooth and gas transfer is slow, reflection of the radar beam is nearly specular (mirrorlike) and the reflected signal is strong. During high wind periods, when waves and turbulent mixing increase the gas transfer rate, the intensity of the backscattered signal is weaker, since the waves act as facets that scatter the altimeter beam randomly in many directions. The backscattered radar intensity thus is inversely proportional to sea surface roughness. We combine knowledge gained from fundamental studies relating surface roughness to gas transfer rate (a National Science Foundation funded project undertaken with Erik Bock and Wade McGillis of the Applied Ocean Physics and Engineering Department) with the altimeter backscatter to make global estimates of the gas transfer velocity as shown above. The orange-red areas in the North Atlantic and the high latitude regions of the Southern Ocean represent high-wind, high-transfer-rate regimes, while the dark blue and purple areas (the equatorial regions) represent low-wind, low-transfer-rate regimes. The new methodology offers the advantage of providing much greater spatial and temporal coverage than can be achieved with buoy or ship-based observations, and it avoids the uncertainties inherent in the model function for gas transfer velocity as a function of wind speed.



Global map shows gas transfer velocity in centimeters per hour estimated from TOPEX/Poseidon altimeter backscatter observed during March 1995

Life Cycles and Population Dynamics

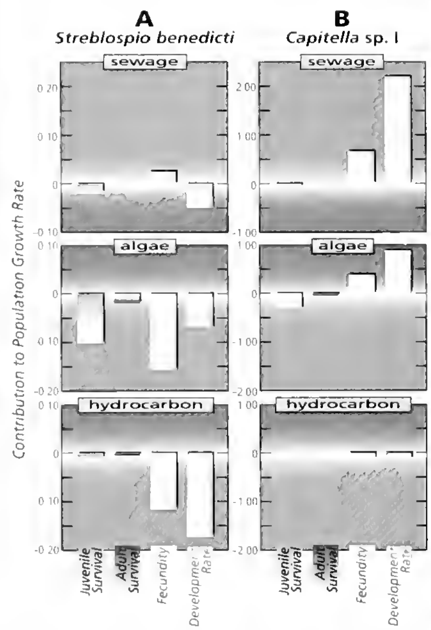
What Role Do Life Cycles Play?

Hal Caswell
Senior Scientist, Biology Department

Populations change because of the birth and death of individual organisms, and the probabilities of birth and death change as an individual develops through its life cycle. This means that mathematical models of population dynamics must include some description of the life cycle in order to capture the mechanisms responsible for population growth or decline. Situations where the environment impinges directly on the life cycle are especially interesting. For example, suppose that a population is exposed to a pollutant. The exposure will produce a complex set of cellular and biochemical responses that affect individual survival, growth, maturation, and reproduction—and, eventually, the growth of the population, causing either a decrease or, in the case of some pollution-tolerant species, an increase.

In a project undertaken with Lisa Levin (a former WHOI Postdoctoral Fellow now at Scripps Institution of Oceanography), we analyzed an experiment on two estuarine polychaetes (*Streblospio benedicti* and *Capitella* sp.I) exposed to fuel oil, sewage sludge, and blue-green algae (all common hazards for species living in polluted or eutrophied estuaries). Exposure to these pollutants had dramatic effects on population growth rate, but the effects and mechanisms producing them differed between species. For example, exposure to blue-green algae reduced the population growth rate of *S. benedicti* (from 1.43 to 1.10), but increased the growth rate of *Capitella* (from 1.79 to 2.55). The biggest contributor to the decline in *S. benedicti* growth rate was a reduction in fecundity, while the increased growth rate in *Capitella* was mostly due to more rapid development. Pinpointing the physiological mechanisms responsible for population-level responses to pollutants is one of the major benefits of this kind of mathematical modelling.

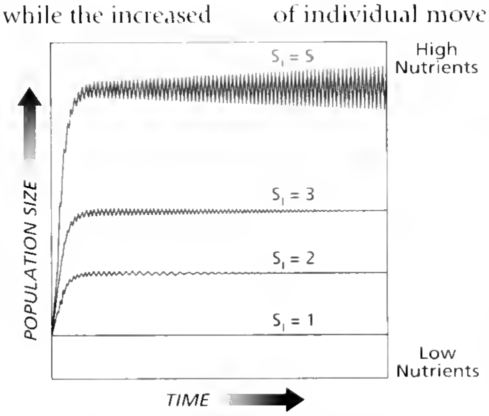
Although polychaetes and other multicellular animals are known to have interesting life cycles, what about the single-celled organisms of the phytoplankton? Their life cycles are defined by the cell division cycle: growth, replication of genetic material, and division. There is evidence that the environment, in the form of nutrients and light, affects the rate of development throughout this cycle. Recent Joint Program graduate Mercedes Pascual-Dunlap and I analyzed the effects of such environmental factors on models of phytoplankton population dynamics. What we found was populations with an increased tendency to oscillate. Nutrient limitation sets up cohorts of hungry cells that develop slowly, thus reducing population growth and allowing nutrient levels to rise. The next cohort of cells benefits from these nutrients and moves rapidly through the cycle, the population increases, and nutrient levels decline, setting the stage for a repeat of the cycle. When these "generation cycles" interact with environmental variation, the result can be complicated, aperiodic fluctuations in phytoplankton populations, fluctuations that occur only because of the interaction of the environment and the life cycle.



Pollution by blue-green algae had different effects on the population growth of two species of polychaetes in the laboratory. *Streblospio* populations grew more slowly, mainly because of reductions in fecundity (left graph). *Capitella* populations grew more rapidly, mainly because of increased development rate.

Funding for the projects discussed has come from the Office of Naval Research, Environmental Protection Agency, and National Science Foundation.

Modeling of population dynamics in terms of individual movement through the life cycle has broad application, including analysis of field and laboratory data and studies of a wide range of organisms both small and large. We have examined larger animal population dynamics in considering the effect of the sink gillnet fishery on the Gulf of Maine harbor porpoise population and are currently seeking funding to analyze the populations of the North Atlantic right whale, the most endangered of the large whales.



Output from a phytoplankton population growth model that includes the cell division cycle. High nutrient levels produce "generation cycles," oscillations that do not occur in traditional models, which neglect the cell cycle.

How a Seal Hears the World

First Recordings from the Seal's Point of View

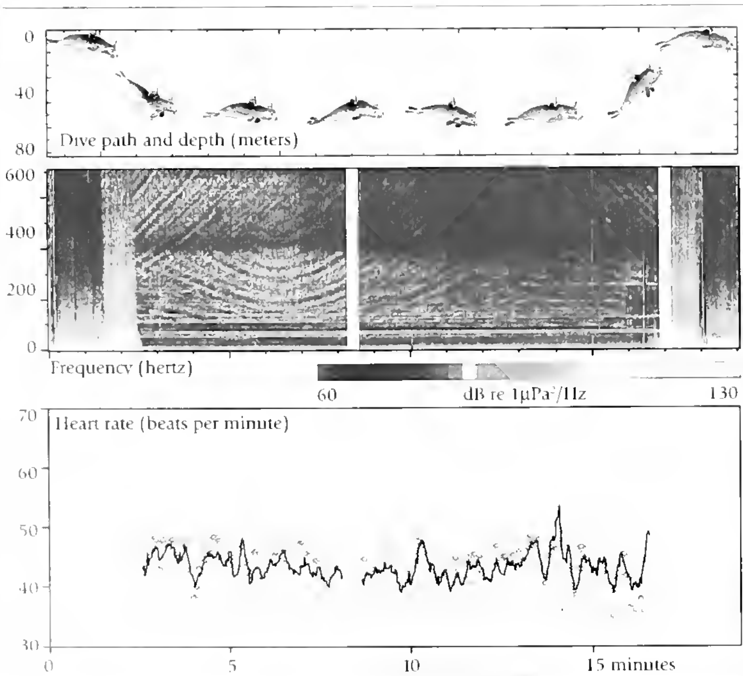
Peter Tyack
Associate Scientist, Biology Department

The elephant seal in the illustration above is equipped with an acoustic data logger that allows scientists to record a variety of information about the animal and its environment. The figure below shows dive depth, acoustic data, and heart rate for one dive as an elephant seal swims across Monterey Bay. Scientists tag and carefully monitor seals that carry the logger to be sure there are no ill effects from participating in the studies.
Seal illustrations by E. Paul Oberlander

For tens of millions of years, marine mammals have been evolving ways to take advantage of ocean acoustics. Whale sounds below the human range of hearing are used for long range communication, and dolphin clicks octaves above it are used to find sonar targets a football field away. In the past 50 or so years, humans have also begun to use underwater sound for communication, to navigate, and to find out about the oceans. This can lead to problems if both humans and marine mammals are trying to use the same channel, for an oceanographer's signal may be a whale's noise. Very loud sounds from underwater explosions, shipping, and industrial activity could harm these animals or disrupt biologically important activities.

The Office of Naval Research (ONR) has initiated research programs both to find out about the influence of low frequency sound on marine mammals and to build research tools for questions that cannot yet be addressed. One of these is a study of elephant seals, which produce low frequency sounds in air and whose ears appear to be sensitive to low frequencies. These animals have been the focus of a long-term study by Burney LeBoeuf and Daniel Costa (University of California, Santa Cruz). Their group has developed remarkable abilities to attach tags to these seals on land and to recover most of the tags after the seals have swum back to their rookery. LeBoeuf, Costa, and I decided to undertake a task many thought impossible—development of a hydrophone tag for recording the low frequency sound environment of a free-ranging marine mammal. Engineering for the project's complex data logger was undertaken by Bill Burgess, a 1993–1994 WHOI Postdoctoral Scholar who is now at the Monterey Bay Aquarium Research Institute. Burgess helped make our idea a reality with an intense engineering effort. He integrated the hardware components, developed software for logging and analysis, and collaborated with the Santa Cruz group on sensor circuits, housings, and attachments.

The figure above left is an artist's conception of an acoustic data logger deployed on an elephant seal. In May 1995, we transported the first seal so equipped to the southern end of Monterey Bay, where the logger was started and the seal was released to return to its home north of Monterey Bay. Imagine how we felt as the housing was removed from the seal and we drove back to the lab to see whether there was any data. In fact, the success of the deployment was beyond our wildest dreams! The device logged swimming speed, depth, temperature, and acoustic data below 1 kilohertz from every fourth dive as the seal swam back to its rookery. The figure at left is a sound spectrogram, a plot of sound frequency against time, during one dive to 60 meters. The seal's breathing on the surface is indicated in red at left and right. Flow noise increases as the seal dives; augmenting the time resolution of this segment reveals each flipper's swimming strokes. Comparison of the noise floor of our logger and low frequency hearing of the one elephant seal tested suggests that we can hear most everything the seal hears at these frequencies. The pattern of blue and green lines in the middle of the spectrogram indicates a boat passing above the seal, and the data include many different ambient noises. When the seal was quiet at the surface or bottom of a dive, there is a signal that sounds like heart beats, and the data points at the bottom of the figure show the heart rate of the seal estimated from these sounds as the boat passed overhead. The next step will be to deploy acoustic data loggers on many seals to evaluate both what the animals hear and how they respond to natural and artificial noises in their world.



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A-II Sails Off into the Sunset

After a Remarkable Million Mile Career

Atlantis II is all decked out for the September 8, 1962, launch ceremony in Baltimore.

With more than a million miles sailed for science, *Atlantis II* left Woods Hole Harbor under the WHOI flag for the last time July 23, 1996. The ship's distance record is matched by only two other US research vessels, and its total of 8,000 days at sea over nearly 34 years of service is unequalled by any research vessel.

Atlantis II's story began in July 1952 when WHOI proposed to the Office of Naval Research that studies be undertaken "for the development of superior ships for oceanographic research." Over the next several years, two WHOI committees considered various sizes and specifications. A 1959 proposal for a $3 million, 175-foot ship was funded by the National Science Foundation. Further deliberations and additional funding ultimately resulted in a keel being laid on June 18, 1962, for a 210-foot vessel at Maryland Shipbuilding and Drydock Company. The ship was launched that year on September 8 and arrived in Woods Hole January 31, 1963.

Over the next three decades *Atlantis II* transported physicists to the Indian Ocean to study currents and monsoons, allowed biologists and chemists to sample open ocean waters around the world, and carried geologists and geophysicists to mid-ocean ridges for work on plate tectonics and other earth science subjects. The ship aided the search for the sunken US nuclear submarine *Thresher*, and became world famous when *Alvin* dove from its deck to the sunken liner *Titanic*.

Atlantis II's longest voyage, in miles cruised, is also the Institution's longest: Beginning in October 1977, *Atlantis II* carried 187 scientists representing 30 US and foreign laboratories on a 573-day, 80,000-mile cruise.

Tom Kleindinst

As crew members cast off lines, *Atlantis II* pulls away from the WHOI dock for the last time on July 23, 1996.

A majority of the ship's work in the 1990s has been devoted to extensive exploration of hydrothermal vent areas, especially along the East Pacific Rise off Mexico and the Juan de Fuca Ridge off the coast of Oregon. Scientists diving in *Alvin* first sighted the vents in 1977 on the Galápagos Rift, and work aboard *Atlantis II* constitutes a major contribution to the understanding of geochemical and biological processes at work on the mid-ocean ridges.

Atlantis II will continue its career with a new name and a new owner, who plans to operate it commercially to support fisheries investigations in the Pacific and Gulf of Alaska regions. The ship's long service to every discipline of oceanographic science concluded with a July 23 decommissioning ceremony on the WHOI pier. It was a day for telling sea stories, renewing friendships made at sea, and celebrating an oceanographic job well done. Farewell, *Atlantis II*!

Dean Conger © National Geographic Society

This National Geographic photo of *Atlantis II* in the Black Sea was taken in 1969. The Caucasus Mountains form the Backdrop.

*A 24-page special edition of the *WHOI Newsletter* details the ship's history in word and photo. Subject to availability, copies may be requested from the *Oceanus* office (see masthead on page 2)

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encompasses a wide variety of shapes and forms. Our cover animals are larvae or early life stages that often differ significantly from the appearances they will take as adult animals. They are considerably magnified here. Many are normally visible only through a microscope or barely to the naked eye, though the long-armed fellow just below the nameplate could be up to a centimeter long (one-eighth the size shown). The artists are Rudy Scheltema, whose article on taxonomy appears on page 16, and Isabelle Williams, who drew the crab larva at left below.

Counterclockwise from below left, the animals are the zoea larva *Portunus sayi* (a Sargasso Sea crab), the ophiopluteus larva of an unknown brittle star species from the tropical Atlantic, the swimming gastropod veliger larva of *Alaba* sp. (a minute snail) from the tropical eastern coast of Australia, the larva of an unkown species of phoronid worm from the central tropical Pacific, the tornaria larva of *Ptychodera flava* (an acorn worm) from the Caribbean and tropical Atlantic, the larva of the brachiopod species *Glottidia pyramidata* (a lantern shell) from the Gulf Stream, the pelagosphaera larvae of *Sipunculus polymyotus* (a peanut worm) from the Gulf Stream, the gastropod veliger *Bursa ?thomae* from the tropical Gulf Stream, the serpulid polychaete *Hydroides dianthus* (a tube worm found in Woods Hole waters), and the mitraria larva of an oweniid polychaete worm found in the warm Gulf Stream.