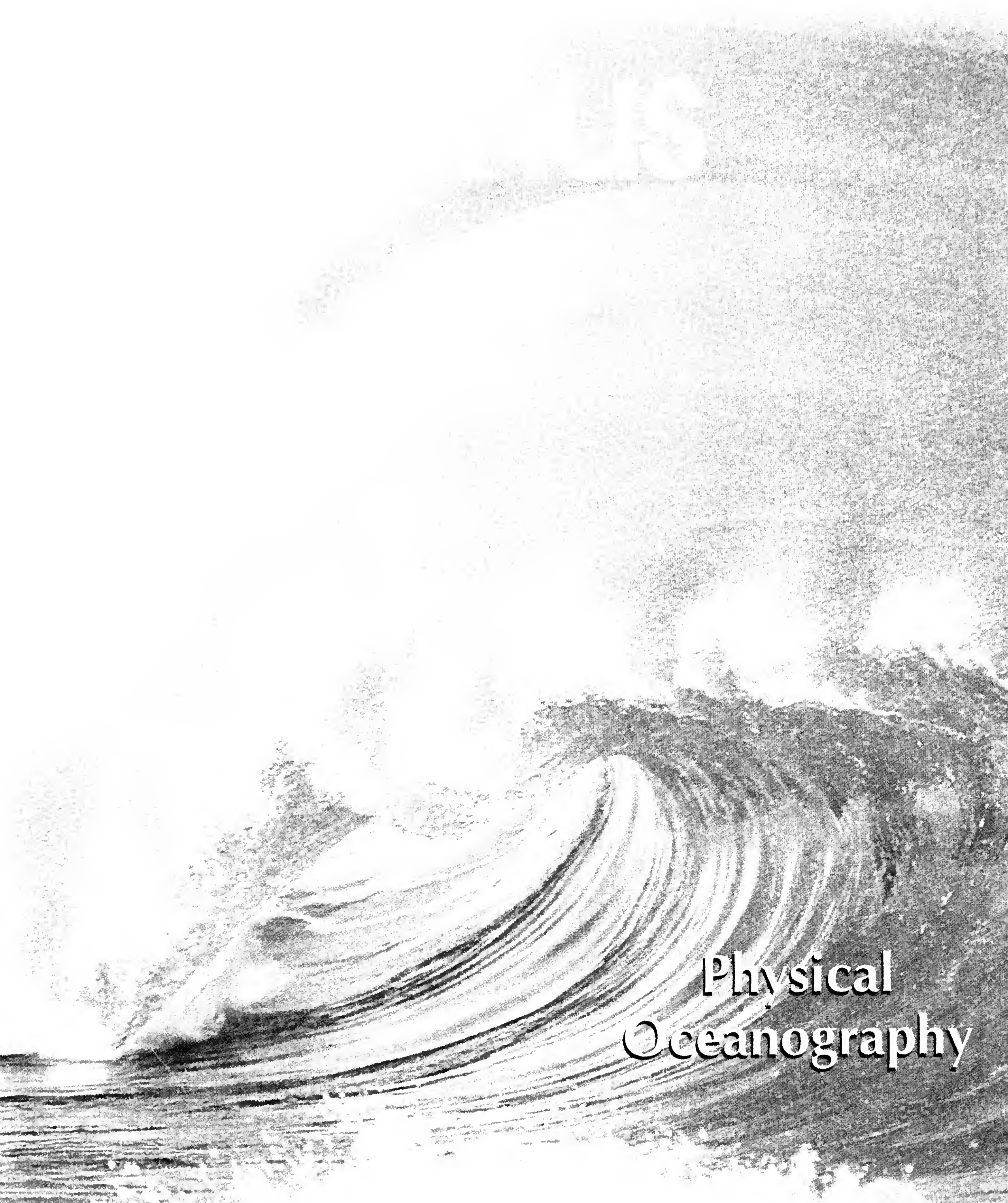
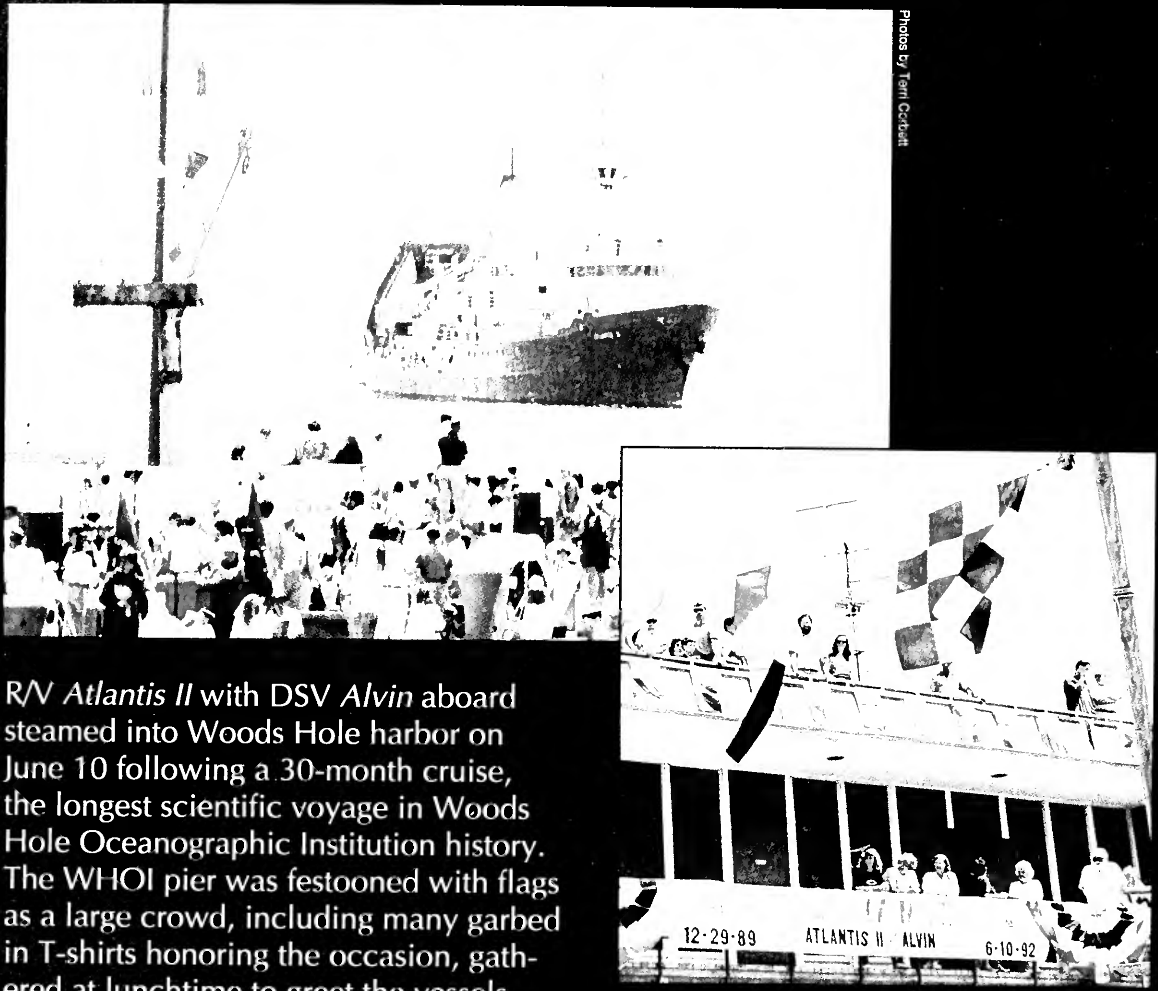


Physical Oceanography

R/V *Atlantis II* & *Alvin* Come Home



Photos by Terri Corbett

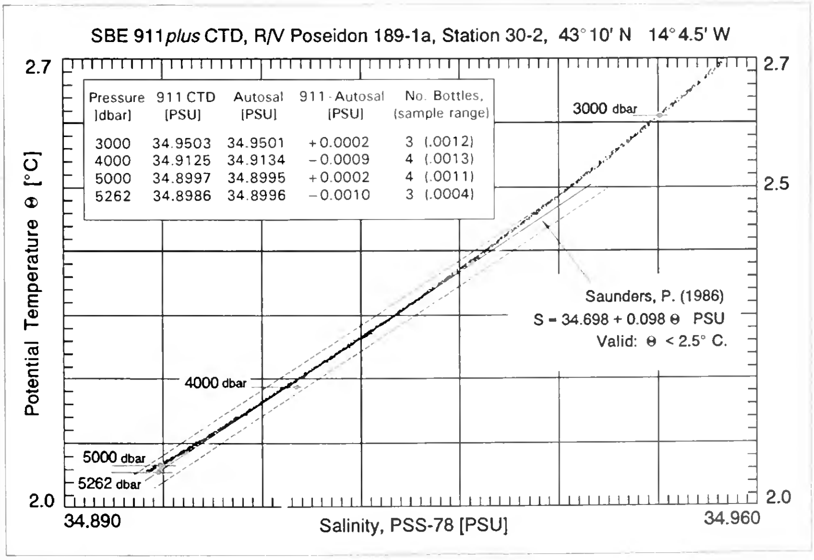
R/V *Atlantis II* with DSV *Alvin* aboard steamed into Woods Hole harbor on June 10 following a 30-month cruise, the longest scientific voyage in Woods Hole Oceanographic Institution history. The WHOI pier was festooned with flags as a large crowd, including many garbed in T-shirts honoring the occasion, gathered at lunchtime to greet the vessels. The 44 "legs" of *Atlantis II* Voyage #125 included 575 days at sea and 368 *Alvin* dives, at locations from the Mid-Atlantic Ridge to the Juan de Fuca Ridge, the East Pacific Rise, and Guaymas Basin.

Sea-Bird Wins in CTD Trials

In May 91 Canada's Bedford Institute of Oceanography performed comprehensive lab and at-sea comparisons of EG&G, Guildline, and Sea-Bird CTD systems. Bedford's conclusion that the Sea-Bird "has the intrinsic resolution and accuracy needed for WOCE-standard work" resulted in purchase of Sea-Bird 911*plus* CTD systems for their deep-ocean hydrographic program.

In similar trials conducted in January 1992 by Germany's Institut für Meereskunde/Kiel, our *911 plus CTD* again outperformed all other participating systems - including the EG&G Mark 5, NBIS Mark 3, and FSI Triton. The T-S plot below is representative of the superb results consistently obtained with the Sea-Bird CTD System during the IFM/Kiel intercomparison.

IFM/Kiel test results include overlaid down-and-up profile plots of *911 plus* data closely matching the historic Θ-S relationship in the N.E. Atlantic (Saunders, 1986, JPO, v.16(1)), and falling within the 0.002 PSU rms tolerance (dashed lines) of the Saunders parameterization. The 48-scan averages plotted below were obtained from raw 24 Hz full-rate data; there has been no editing, fitting, or post-correction of any kind. The data agree to within 0.001 PSU with averaged bottle values from 3000 to 5262 dbar (table and dots), and to better than 0.003 PSU with *every* bottle from 0 to 5262 dbar.



Pressure]dbar]	911 CTD [PSU]	Autosal [PSU]	911 - Autosal [PSU]	No. Bottles, (sample range)
3000	34.9503	34.9501	+0.0002	3 (.0012)
4000	34.9125	34.9134	−0.0009	4 (.0013)
5000	34.8997	34.8995	+0.0002	4 (.0011)
5262	34.8986	34.8996	−0.0010	3 (.0004)

SBE

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Bellevue, Washington, 98005 USA
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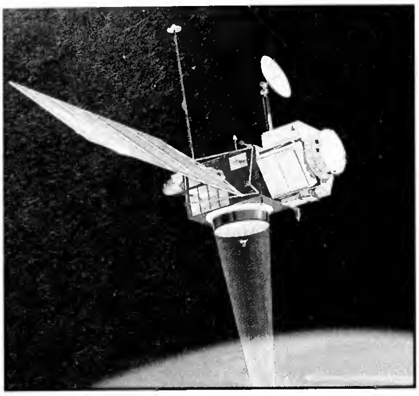
PHYSICAL OCEANOGRAPHY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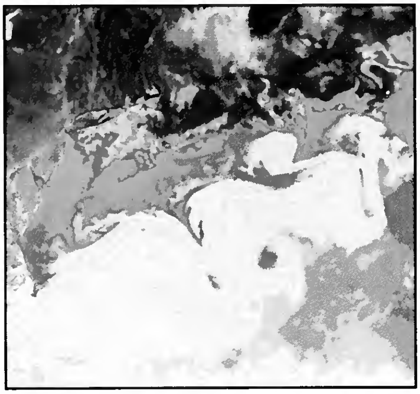
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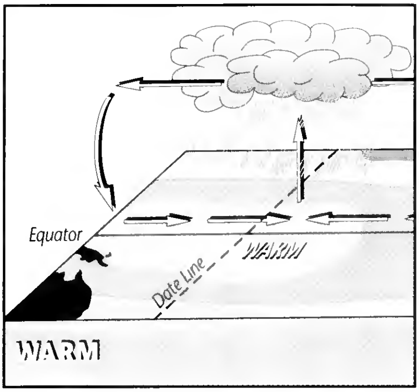
Oceanus (ISSN 0029-8182) is published in March, June, September, and December by the Woods Hole Oceanographic Institution, 9 Maury Lane, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts, and additional mailing offices. POSTMASTER: Send address change to Oceanus Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217-6419.

Headings and Readings



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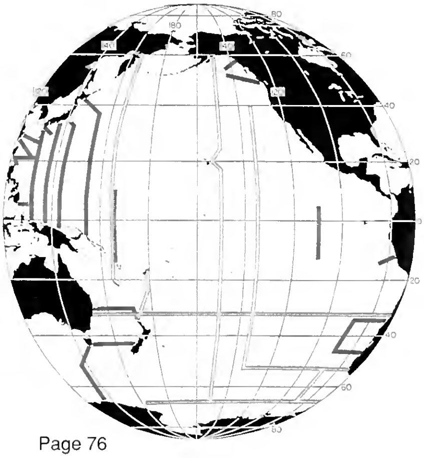

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As everything on Earth is held in an intricate web of physical laws, a thunderous ocean wave represents the whole complex, fascinating field of physical oceanography.

Photo © 1988 Don King, Lightwaves, Haleiwa, Hawaii

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The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of *Oceanus* magazine or its publisher, the Woods Hole Oceanographic Institution.

Editorial responses and advertising inquiries are welcome. Please write:
Oceanus Magazine
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543,
or telephone: (508) 457-2000, extension 2386.

Members within the US, please write: *Oceanus* Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217-6419, or telephone, toll free: 1-800-825-0061 for subscription-related questions. Individual membership rate, $25 per year; Students, $20; Libraries and Institutions, $35. For Canadian subscriptions, add $5 to basic rates.

Single current issue price, $6.25; 25% discount on orders for five or more. Back issues are available for $9 ($8 each plus $1 shipping and handling). Please make checks payable to the Woods Hole Oceanographic Institution.

Subscribers outside the US, please write: *Oceanus*, Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 2RU, England. Individual subscription rate: £25 per year; Students, £16; Libraries and Institutions, £47. Single-copy price, £9. Please make checks payable to Cambridge University Press.

When sending change of address, please include mailing label. Claims for missing numbers from the US will be honored within three months of publication; overseas, five months.

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Oceanus

International Perspectives on Our Ocean Environment
Volume 35, Number 2, Summer 1992 ISSN 0029-8182

Published Quarterly as a benefit of the Woods Hole Oceanographic Institution Affiliates Program

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ISSN 0029-8182/83 $2.00 + .05. GST R 128 372 067.

From the Editor

An Author is Missing

Renowned physical oceanographer Henry Stommel wrote several articles for *Oceanus* over the years. Most recently, he described the Slocum Project, a plan to use globe-circling floats to telemeter data from far-flung locations (*Oceanus*, Winter 1989/90), and contributed a profile of his Slocum collaborator and neighbor Doug Webb (*Oceanus*, Spring 1991). He agreed in January to write about salt oscillation for this issue. "That would be fun," he said.

A few days later one of the great lights of physical oceanography dimmed when Hank died. So, instead of enjoying a description of his current work in this issue, we are preparing a special edition of *Oceanus* to celebrate his career. It will be published in September, and an article on salt oscillation written by Hank's principal collaborator on this subject, William Young of the Scripps Institution of Oceanography, will be included.

Hank Stommel's influence on physical oceanography was immense. In their preface to *Evolution of Physical Oceanography, Scientific Surveys in Honor of Henry Stommel*, published in 1980 to honor Hank's 60th birthday, colleagues Bruce Warren (Woods Hole Oceanographic Institution) and Carl Wunsch (Massachusetts Institute of Technology) wrote "the originality and penetration of his own research . . . in major part, has generated the modern concepts of ocean circulation." He had a special talent for finding the simplest model of an underlying physical process and exposing its essence.

The range of his some 120 professional publications spanned nearly all aspects of both theoretical and observational physical oceanography and extended into cloud physics, limnology, and estuarine circulation. Hank's prolific intellect produced more scientific questions than he could ever answer himself, and with enthusiasm and intellectual vigor he stimulated many investigators to follow lines of inquiry that promised to be fruitful and revealing—hence although his light has dimmed, it has not gone out.

The range of his avocational interests was also prodigious: gentleman farmer, amateur painter, oriental chef, marine antiquarian, musicboxicologist, as well as amateur railroader, home printer, and explosives aficionado. As neighbors, my family knows something of the latter three. When our elder son reached toddlerhood, several home-printed tickets arrived in our mailbox for rides on the small railroad that circles the Stommel garden. And on the Fourth of July, as well as at midnight of a New Year's Eve, the neighborhood would reverberate with Hank's explosive concoctions!

In the 1950s, Hank's printing press was the source of a variety of puckish announcements, notices, and invitations at the Woods Hole Oceanographic Institution. It was also employed for scientific pamphlets—a paper entitled "Why Do Our Ideas about the Ocean Circulation Have Such a Peculiarly Dream-Like Quality?" is considered seminal by Hank's colleagues, though it was never published other than by the Stommel "underground press."

Hank's career began and ended at WHOI. In between, he was a faculty member at Harvard and then MIT, but his fundamental ties were in Woods Hole. We are pleased to be assembling a collection of tributes from his colleagues and a sampling of his work and his writing. Readers who want to obtain a copy of this volume may refer to page 35 for further details.

In 1974, the Institution selected Hank to receive the Bigelow Medal. My personal favorite of Hank's comments is drawn from his acceptance speech: "Most human history has not afforded men much chance to pursue their curiosity, except as a hobby of the rich or within the refuge of a monastery," he said. "We can count ourselves fortunate to live in a society and at a time when we are actually paid to explore the universe."

Vicky Cullen

Oceanographer's Toolbox

Surface Current Trackers of the World's Oceans

WOCE/TOGA Lagrangian Drifters

Laurence Sombardier

Most surface-current maps are based on observations of how ocean currents cause ships to drift off course. By the end of the 19th century, geographers had mapped and named all the major western boundary currents and tropical ocean-current systems. Because ships sail primarily on great circular routes between major ports, even today we do not have enough ship-drift data to make realistic surface-current maps for almost 80 percent of the ocean surface. Ships drift under the combined action of wind forces (above the waterline) and current effects (below the waterline) on the vessel's hull, and even in the absence of wind, ship drift must be interpreted as an average of water movement in the upper ocean. Because of their varying configurations, each ship drifts at a different speed relative to the currents and wind. The uncertainty in this type of data is a drift of 0.5 nautical miles per hour, or 25 centimeters per second, which is faster than the surface circulation of most of the ocean!

Oceanographers have used drifting objects to measure ocean currents for over 100 years. Drift bottles have been the most common choice; records of their launch and recovery sites give some idea of ocean surface currents but no hint of the path taken between launch and recovery. These devices typically consisted of a surface float that contained a transmitter and an antenna tethered to a subsurface drogue that acted as a drag element. Global tracking of transmitters on the ocean surface via the ARGOS satellite (launched some 20 years ago) prompted a proliferation of imaginative drifting buoy designs. Drogues included World War II surplus parachutes, canvas tubes and window shades, sailcloth cylinders, wooden and metal crosses, and star-shaped kites. Surface floats were metal cylinders, plastic jugs and cones, discs and spherical shapes, or any combination of the above.

Some drifters weighed a few pounds and floated with several inches of purchase, while others weighed 500 pounds and employed massive cargo parachutes at 100 meters depth. Oceanographers believed that the drift of these devices represented water motion better than the drift of ships. In 1988, at the Global Drifter Center (GDC) at Scripps Institution of Oceanography, we began to design a drifter for global deployment from ships or airplanes to measure currents in the ocean's mixed layer as accurately as can be done with a modern current meter.

The GDC drifter was designed with the following criteria in mind:

- known water-following capability,
- durability at sea for more than a year,
- low cost,
- ease of manufacture, and
- ease of deployment.

It was developed in response to the needs of the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Programme (TOGA) for accurate surface-current measurements. Over 800 of our WOCE/TOGA Lagrangian Drifters have been released into the ocean by a joint WOCE and TOGA Surface Velocity Programme, as well as by many federal agencies that need accurate surface-current measurements. Because the drifter design is standardized, all the ocean-drift data gathered by a multitude of programs is now interchangeable.

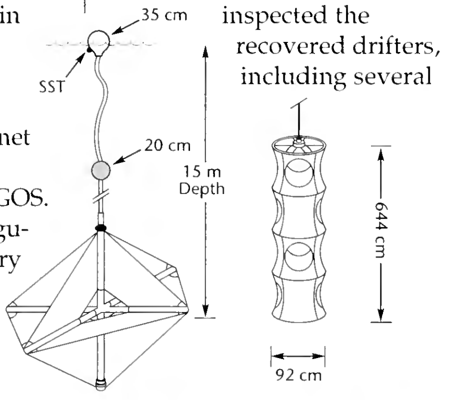
The WOCE/TOGA Drifter Design

Two drogue designs were tested: the Ministar and the Holey Sock. Both retain their shape under different current conditions, and have large drag coefficients that help reduce "slip," the drogue's relative motion through the water. To measure slip, we attached one current meter to the top of the drogue and another to the bottom. If the current meters recorded no relative motion, the drogue was not slipping through the water. After more than 60 two- to four-hour deployments at sea in varying wind and current conditions, we found that slip was primarily caused by wind and the velocity difference between the drogue and the surface float.

To reduce this slip, the drogue had to be as large a drag element as possible, and the surface float and tether had to be as small and slippery as possible. This discovery was hardly a surprise to the engineers who had been building ARGOS-tracked drifters for the past two decades; however, it was surprising just how large the drogue had to be so that the drifter would follow water to match the precision of modern current meters. By fine-tuning the drogue size, we have developed a drifter that follows water motion to an accuracy of 1 centimeter per second in winds of 10 meters per second. The Ministar and the Holey Sock designs perform similarly at sea; however, the Holey Sock is easier to construct and deploy, leading us to adopt it as our standard.

For ease of handling, the Holey Sock drogue is folded into an accordion that is held together by paper tape. The tether is coiled around a cardboard cylinder and the magnet (whose removal switches on battery power through the surface-float hull) is also attached with paper tape. This drifter weighs about 55 pounds in air, so one able-bodied seafarer can easily throw it into the water from the stern of a vessel at full speed. After a few hours in the water, the paper tape dissolves, the drogue deploys itself below the surface float, and the magnet falls off, initiating satellite transmission through ARGOS. Holey Sock drifters are regularly deployed by voluntary observing ships as well as oceanographic research vessels. The US Navy and Coast Guard are also deploying some by aircraft, thus opening the possibility of deployments in remote ocean areas.

To determine the potential causes of degradation in the mechanical components of our drifters, especially the tether, 12 drifters were recovered off the coast of Washington after more than 200 days at sea, as part of the WOCE Heavy Weather Tests. We inspected the recovered drifters, including several



Ministar Drogue

Holey Sock Drogue
(Official WOCE/TOGA SVP Drifter)

Schematic by Jayne Doucette/WHOI Graphics

Good water-following capability was achieved with the Ministar and Holey Sock drogue designs. The surface float is a 35-centimeter-diameter fiberglass sphere that houses the ARGOS satellite radio transmitter, antenna, batteries, sea-surface temperature sensor, and a submergence sensor that reveals whether the drogue is still on or has fallen off. A polypropylene-impregnated wire tethers the float to the drogue 15 meters below. On the tether is a 20-centimeter-diameter spherical float that isolates the drogue from the vigorous action of wind waves felt by the surface float.

designs of tethers, drogues, and attachment methods, and decided to use polypropylene-coated tethering cables and flexible carroting around all tether attachment points. (Carroting is the addition of urethane to float attachments; the urethane tapers off, providing a carrot-like shape around the tether.) Because lithium batteries had unpredictable failures, they were replaced by alkaline batteries. These design changes made the drifter more expensive, but the cost increase was more than offset by the significant improvement in drifter survivability, from an average half-life of 220 days for drifters deployed from 1988 to 1990, to over 400 days for those deployed since 1990.

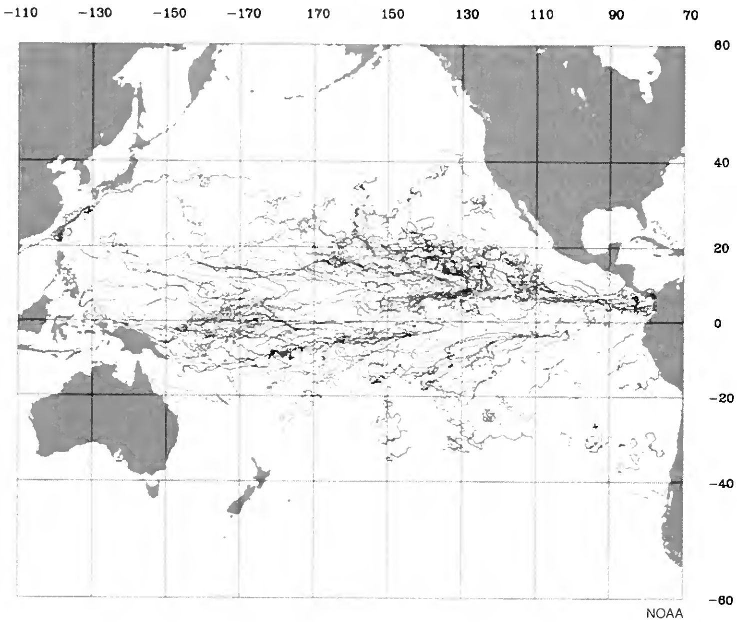
Future Measurements with Drifters

Systematic deployments of our drifters commenced in the tropical Pacific for TOGA in 1988, and Pacific Ocean deployments for WOCE began in 1991. By the end of 1992, the entire Pacific will be seeded with 420 WOCE drifters covering 600 square kilometers. Deployments started in the Atlantic Ocean in 1992, and the Southern and Indian oceans will be seeded from 1993 to 1997. We plan to obtain at least a four-year data set from each of the global ocean basins.

After the WOCE/TOGA drifter program winds down in 1997, a more permanent array of drifters in the world's oceans is planned by the Global Ocean Observing System to monitor changes in the oceans for many years to come. In addition to providing accurate sea-surface temperatures and ocean-current measurements, many other uses have been developed for WOCE/TOGA drifters; for example, drifter data has been used to study materials dispersion at sea, fish larva recruitment, iceberg movement, and weather prediction. Reports of large amounts of tuna being caught around the WOCE/TOGA drifters in the eastern tropical Pacific has interested several fisheries in using these drifters for fish-aggregating devices. The GDC is also adapting salinity sensors for use on the tether, and attaching barometers to the surface float. Several oceanographers are mounting ocean-color sensors on these drifters for measuring chlorophyll in the oceans.

In five years, we expect to have enough data from the WOCE/TOGA drifters to begin to construct new, accurate maps of surface-water movements of the world's oceans.

Laurence Sombardier is Manager of the Global Drifter Center at the Scripps Institution of Oceanography.



These trajectories represent all the WOCE and TOGA drifters deployed in the Pacific Ocean in 1991.

Observing Ocean Circulation from Space

Carl Wunsch

One of the major reasons oceanography has a flavor all its own lies in the brute difficulty of observing the oceans.

Physical oceanography is a branch of fluid dynamics with problems and flavors all its own. Its practitioners seek to understand why, where, and how water moves, on all space and time scales, and the consequences of these movements for a vast variety of purposes. Progress toward this understanding requires a particularly intimate partnership between theory on the one hand, and observations and experiments on the other. Although the equations governing fluids are known, fluid flows have many possible structures, and their solutions are so varied that theoreticians are guided to a great extent by observations. But the process is a two-way street—again, because fluid flows are so rich and varied, the experimentalist or observer requires a theoretical structure to describe and understand the myriad of physical situations that arise in the laboratory.

One of the major reasons oceanography has a flavor all its own lies in the brute difficulty of observing the oceans. The problem of studying a global-scale fluid is extremely challenging even under the best circumstances. Although Earth scientists speak (sloppily) of their "experiments," normal experimentation, where scientists carefully control the conditions of their observations, is usually impossible. The "laboratory" is Earth. Nothing is controllable, and although scientists "observe" or run expeditions, they rarely conduct experiments in the usual sense of the word.

Apart from its intimidating size, the ocean presents some forbidding observational difficulties. Taking oceanographic data requires instruments to survive enormous pressures (up to 600 atmospheres) and the corrosive conditions of a fluid that is 3.5 percent salt (by weight). In contrast, measurements in space or the atmosphere encounter neither pressures exceeding 1 atmosphere nor such extreme corrosive media.

But the central difficulty arises because of the sea's opacity to electromagnetic radiation (light and radio waves). The salt content of the ocean renders it a conductor, and this conductivity "shorts out" light and radio waves, typically within a few millimeters of their sources. Why is this such a formidable difficulty? The problem can perhaps be best appreciated by considering how one observes the sister global fluid, the atmosphere. Meteorologists have a complex array of observational tools—balloons, aircraft, satellites, rocket profilers. Consider that every one of these instruments relies in one way or another upon the ability of light and radio waves to propagate through the atmosphere: The balloons and profilers return their measurements to the ground through small radios, and electromagnetic radiation recorded by satellites results in cloud pictures and measurements of atmospheric temperature structure. All these means are denied to oceanographers. Observations from space can measure only the sea surface, and measurements made within the ocean's volume cannot be returned to the scientist making them, except through direct physical contact.

During a century of observational physical oceanography, these problems have dictated very specific methods of observation. The physical oceanographer's first, and still central, tool is the ship. With ships, one can lower instruments into the ocean, and either record measurements in the instrument (initially through clever mechanical devices like reversing thermometers and clock-driven strip charts, and later through electronic devices) or send electrical signals up a cable for shipboard recording.

With the advent of modern solid-state electronics, a whole range of new devices for observing the ocean emerged, including internally recording current meters, neutrally buoyant floats, and profiling devices. But with some rare exceptions, all these devices still either hang on the end of a cable that transfers measurements to a ship or are left behind to record information and be recovered later, also by ship.

Discussions of the possibilities for using spaceborne observations began just after the USSR launched Sputnik in 1957.

About 20 years ago, partially as a result of measurements from this multitude of new techniques, it became clear that the ocean is intensely turbulent, and that it makes no sense to regard it as a steady, unchanging system. Measurements made from a ship cannot be made as fast as the ocean changes. Consider, for example, that a modern oceanographic vessel moves no faster than a rather sluggish bicyclist (10 to 14 knots). At this pace, it takes a ship two or more months to cross the Pacific Ocean, stopping along the way to observe, and the ocean system changes in many ways during that time. Furthermore, with this strategy only one line across the ocean is measured, leaving oceanographers with little or no idea what was happening even 50 kilometers from where they made their observations. In addition, the nature of oceanic variability and turbulence is on such a small spatial scale (about 50 kilometers for major changes) that even the new generation of very clever measuring devices could never be produced in numbers adequate to observe the changing fluid. The problem is a combination of financial and human costs. Measurements at sea, whether from ships or from self-contained instruments, are very expensive. (The daily charges for WHOI's R/V *Knorr* are now $18,500 per day, not including the costs of the scientific party or the instruments themselves.) It is unlikely that ocean scientists will find the money or human resources to greatly increase the number of research vessels at sea, or to produce and maintain many thousands of new in situ devices.

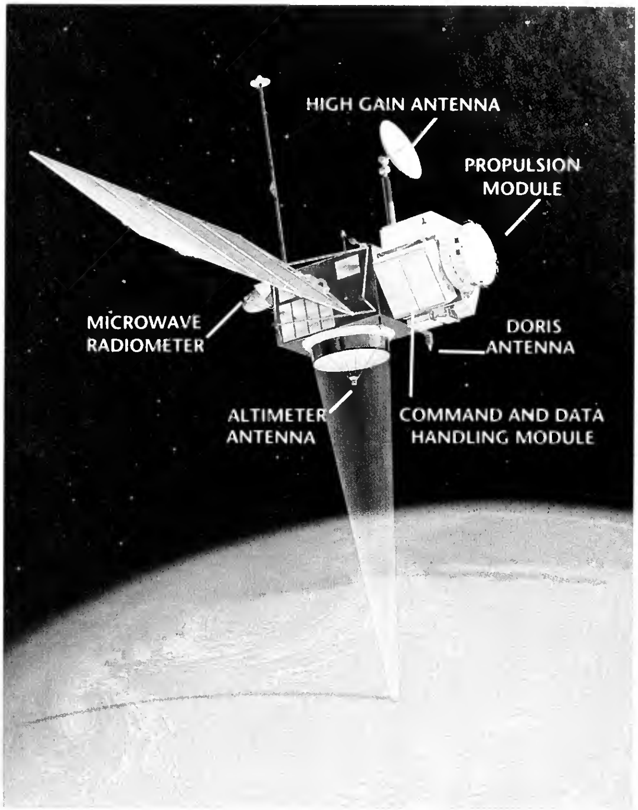
Satellites Offer a Broad View Oceanographers Need

The oceanographic community needs new observational methods to respond to the ever-greater demand for information about the global consequences of ocean circulation, such as climate, sea-level rise, fisheries collapse, and so forth. For example, that oceanographers do not really know today's oceanic circulation with any degree of accuracy means that we cannot seriously attempt the climate forecasts we are increasingly asked to perform (an analogy is the problem of forecasting tomorrow's weather in Boston, in complete ignorance of today's). A number of routes to new observational technologies are being explored, including acoustical methods such as tomography and "unmanned ships." Another conspicuous contender for large-scale observations immediately suggests itself—orbiting spacecraft. Indeed, discussions of the possibilities for using spaceborne observations began just after the USSR launched Sputnik in 1957.

The problem, however, is the one already mentioned: Devices in satellite orbit that rely on electromagnetic radiation for measurement cannot see below the sea surface. Because the ocean depth averages more than 4,000 meters, the obviously measurable sea-surface properties are not necessarily of vital concern to scientists interested in the behavior of the entire ocean, top to bottom. Unfortunately, it is not easy to interpret readily measured quantities like sea-surface temperature in terms of the behavior of the 4,000-meter water column below. The physics of the very upper skin of the ocean, the depth to which the unusual infrared and microwave measurements are confined, is one of the most complex of all oceanic regions; it is in constant and complicated interaction with the atmosphere, and its structure is not easily related to oceanic temperatures even 1 meter deep.

In the search for spaceborne observations that carry information about the whole oceanic water column, one is led almost from the beginning to the possibility of measuring the shape of the sea surface. The attraction of this measurement is not difficult to understand. If the fluid ocean were at rest, the sea surface would be perpendicular to the local force of gravity everywhere, as it is in a resting cup of coffee. But because the sea is in motion, the sea surface is deflected relative to gravity. Consider that if one sets a cup of coffee swirling by stirring it with a spoon, the fluid surface at the edge rides higher than that at the center. With a measurement of the shape of the coffee's surface (along with the assurance that the physics are known—that is, one expects that the centrifugal force of the swirl and the pressure owing to the tilt of the coffee surface are nearly balanced), it is possible to work out the fluid velocity from top to bottom with considerable accuracy.

In the sea, elementary physics leads us to conclude that if we look at slowly changing motions (on time scales longer than about one day) over big enough distances (on spatial scales larger than about 50 kilometers),



The TOPEX/POSEIDON satellite is expected to be launched in July 1992. Basic measurements are made by the altimeter antenna. Various other antennas are used for tracking and communication. The microwave radiometer measures the water vapor content of the atmosphere in the path of the altimeter signal to correct the measurement. Propulsion and control modules keep the satellite in optimal orientation and orbit. (Courtesy of L. Fu, Jet Propulsion Laboratory.)

then the sea-surface tilt can be used to compute the moving fluid's speed and direction. As in the coffee cup, the surface tilt generates pressure differences in the fluid below. Unlike the coffee cup, the force balance is not between the pressure forces owing to sea-surface tilts and centrifugal forces, but between pressure forces and Coriolis forces (which are generated by Earth's rotation and move water to the right in the Northern Hemisphere, to the left in the Southern Hemisphere) except near the equator. The details of this relationship need not trouble the reader, however; it suffices to accept the postulate that if we know the tilts of the sea surface we can calculate where, how fast, and in what directions the fluid is moving.

If we know the tilts of the sea surface we can calculate where, how fast, and in what directions the fluid is moving.

Readers of newspaper weather maps may recognize the atmospheric analogy. These maps often indicate positions and intensities of barometric highs and lows. Knowing that the force balance, as in the ocean, is between pressure forces and Coriolis forces permits meteorologists to infer that wind motion is clockwise around the highs, and counterclockwise around the lows (and is reversed in the Southern Hemisphere). In the sea, elevation and depression of the surface, relative to where it would be in a resting ocean, are the oceanographer's highs and lows. If such measurements of the sea can be made, their most intriguing aspect is that they permit oceanographers to make powerful inferences about the ocean at depth, not just at the sea surface.

Meteorologists have long known that barometric observations at Earth's surface permit strong inferences about what is going on far aloft. That is, surface pressure fluctuations reflect pressure fluctuations to a considerable altitude. The same effect occurs in the ocean: Determining how far down and how accurately one can infer the pressure field requires a study of the fluid-dynamics equations, but analysis leads to a result that can be summarized fairly simply. First, we know as a general rule that the pressure field cannot change rapidly in the very upper ocean the way the temperature field can—it can only evolve in the vertical, slowly and smoothly. Second, the distance over which it evolves in the vertical depends on the lateral extent of the disturbance, the strength of the ocean stratification (that is, how rapidly the water density changes with depth), and the latitude. For disturbances that are, say, 100 kilometers across, the sea-surface elevation can be used to calculate the pressure to either about 2,000 meters depth, or over the entire water column, top to bottom. (In the oceanographer's jargon, these would be called "baroclinic" and "barotropic" disturbances respectively.) The same physics tells us that we should be able to distinguish the two different representative depths by watching surface elevation change through time. Top-to-bottom disturbances should evolve much more rapidly than those confined to the upper few thousand meters. If there are no time changes, we have to be somewhat more clever, but there are ways to do it.

These considerations lead us to ask if we can measure the shape of the sea surface from space using "satellite altimetry." The basic concept is delightfully simple: Fly a radar-carrying spacecraft to measure the sea-surface shape, then obtain the pressure field by subtracting the shape the surface would have been were the ocean not moving. If this can be done accurately enough, oceanographers have, for the first time in their history, a tool that permits them to look at the sea in its global entirety and to great depths, at a speed sufficient to catch it before it changes significantly. As the oceanographic community becomes ever more beset by demands for understanding climate and climate change, the need for this capability seems overwhelming.

Making Satellite Altimetry Work

The concept of satellite altimetry is appealingly simple, but in practice it leads to one of the most complex of all oceanographic measurement systems. Some of the problems are fascinating as scientific/engineering problems in their own right, and are worth understanding to appreciate the efforts of the teams of scientists and engineers who make these things work.

We are faced with making a measurement accurate to 1 centimeter at a distance of 1,000 kilometers.

To an observer on the ground, local gravity points "downward," and if the fluid is at rest the sea surface looks flat, the way the surface of a resting cup of coffee would. To an observer in space, Earth looks roughly spherical. Were Earth a sphere of constant internal density, the shape of a resting ocean would also be spherical, easily subtracted from the measurement. But in reality, Earth is not a sphere, and is better described as a "bumpy spheroid." The spheroid isn't much more complicated than the sphere, and is not a problem. It's the "bumpy" part that causes problems. Because Earth's interior is a complicated dynamical system, surface gravity varies considerably from what it would be on a simple body. In particular, the surface to which a resting ocean would like to conform varies vertically by over 100 meters (relative to a smooth reference surface) as latitude and longitude change.

Goddard Space Flight Center scientists have estimated the variation on this "resting ocean surface" relative to a simple underlying reference surface in the figure on page 14. (Earth science jargon calls the resting ocean surface the "geoid," a term I will use for brevity.) Note, for example, a big hole at the southern tip of India, and the strong rise across the North Atlantic. This estimate shows only features that vary over distances of about 4,000 kilometers and longer—that is, it has been averaged horizontally to make it smoother than it really is. Given that we have some estimate of what the geoid should look like, how much should the ocean deviate from it? Or, put another way, how big is our sea-surface tilt signal? The answer comes from existing knowledge about the strength of oceanic currents. Some simple calculations suggest that over the entire global ocean, maximum deviations of the sea surface from the geoid are less than about 2 meters. Thus in order to make satellite altimetry work, the oceanographer must determine deviations of the sea surface, relative to the figure's bumpy surface, of less than 2 meters; further calculations suggest that, to be useful in telling us things we do not already know, the accuracy must approach 1 centimeter. Spacecraft most suitable for altimetric measurements fly about 1,000 kilometers above Earth's surface. We are faced with making a measurement accurate to 1 centimeter at a distance of 1,000 kilometers, or 1 part in 100,000,000.

Even if this accuracy is possible, lots of interesting problems arise. Consider that subtracting the shape of the geoid from the measured distance to the spacecraft only makes sense if we know how high the spacecraft is, to the level of accuracy described above. What affects the height of a spacecraft? Lots of things, such as gravity field variations that make the geoid bumpy, the amount of sunlight hitting it (including how much is reflected back from clouds), and how much atmospheric drag it encounters. Can we determine the orbital radius of a spacecraft that is 1,000 kilometers high to 1 centimeter?

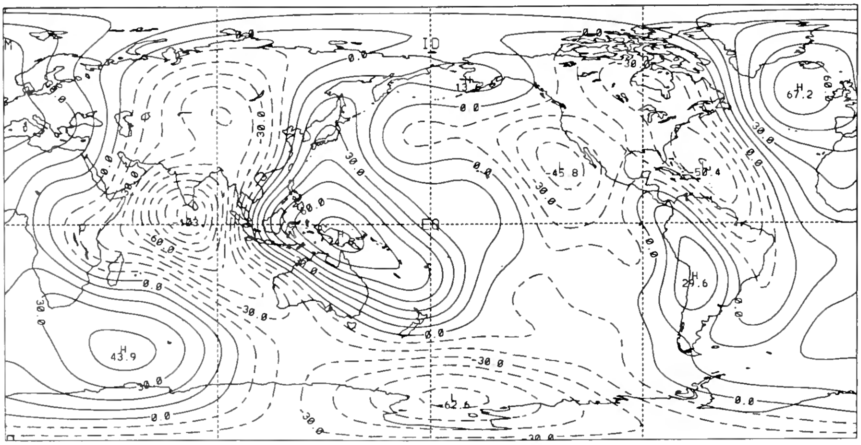
Consider, too, that the atmosphere lies between the sea surface and the spacecraft. Satellite altimeters operate by measuring the round-trip travel time of a radar pulse between the satellite and the sea surface. If the nature of the atmosphere varies, then the travel time can be affected, producing spurious variations in sea-surface elevation. The chief villains are water vapor in the atmosphere and the electron content of the ionosphere.

A host of other problems arise, but they need not detain us here. The complications might lead one to wonder if the whole idea might best be abandoned. But we cannot afford to abandon it: If oceanography is to address many of its outstanding problems, including those of increasingly important societal concern, we need ways to observe the system continually and globally. Furthermore, as I will now try to explain, the problems have essentially all been overcome, and altimetric measurements of the sea surface are a completely practical, if still novel and exciting, new oceanic measurement.

Using Satellite Altimetry

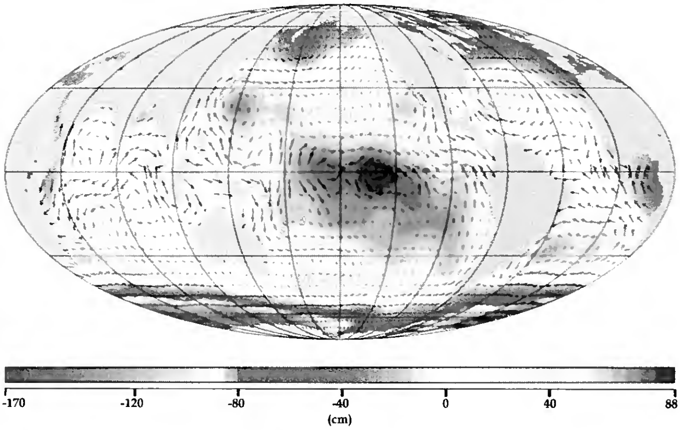
The first radar altimeter in space flew for a few days in the early 1960s on a National Aeronautics and Space Administration manned, orbiting laboratory. The system's measurements were accurate to tens of meters, and it recorded only the largest variations in the geoid's surface. Since then, a series of US-based spacecraft altimeters with ever-increasing accuracy have flown. The most recent of these was a US Navy spacecraft, called Geosat, launched in 1985 not for scientific purposes, but for determining the gravity field at sea to improve submarine-launched missile targeting.

Although the technical configuration of the mission bore little resemblance to what oceanographers would have preferred, it showed that the technology had matured to the point of confirming the fundamental ideas I have described, and the ultimate technical goals had indeed come within reach. Scientists in the US and abroad have worked



A. *This estimate was made by NASA Goddard Space Flight Center scientists of Earth's gravitational field, relative to a smooth underlying "reference Earth." Only long wavelength components are shown here. If the ocean circulation were brought to rest, the sea surface would be expected to display this shape (relative to the underlying reference surface), usually referred to as the "geoid."*

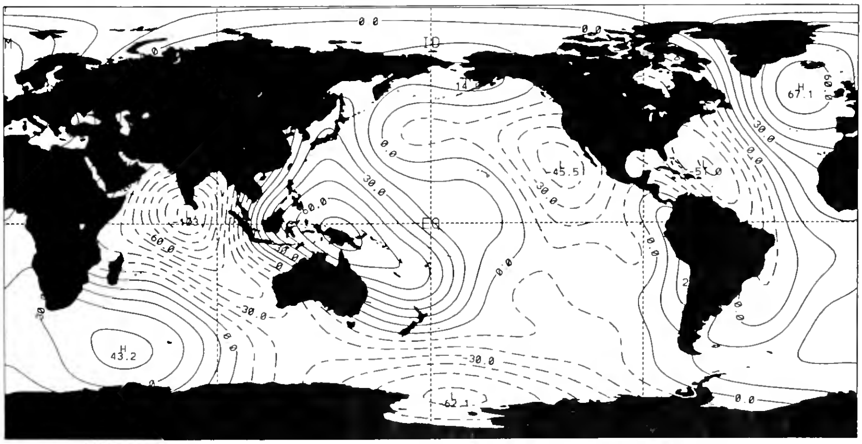
diligently to exploit these altimetric data, reducing the error sources and learning how to use data very different from those familiar to oceanographers. Consider some of what has been accomplished.



The difference between the geoid (Figure A) and the actual sea-surface elevation (Figure B) is the deflection caused by ocean circulation. From this, sea-surface topography may be estimated, as this map shows. In principle, such estimates are derived by subtracting Figure A from Figure B; in practice, the calculation is more sophisticated and indirect. Many known major features of ocean circulation are evident—for example, the large gyral circulations of the subtropical Atlantic and Pacific and the Circumpolar Current. These features extend to great depth in the ocean. (Courtesy of S. Nerem, Goddard Space Flight Center.)

Figure B shows the sea-surface elevation relative to the same reference surface used in Figure A, as determined from Geosat altimetric measurements. The remarkable resemblance of the two figures shows that a comparatively crude altimetric mission can measure the shape of the sea surface to an accuracy of some tens of centimeters. The difference between the two should be the quantity we seek, as the difference between the geoid and the actual sea-surface elevation is the deflection caused by ocean circulation. Such a computation has been carried out by various groups in the US and Europe. Highs and lows appear roughly as anticipated from the known characteristics of ocean circulation and inferred flows. There are also troublesome features, believed to be lingering Geosat errors (to reiterate, Geosat was not designed for this purpose) and errors in knowledge of the geoid. Nonetheless, two surfaces with variations of 100 meters or so have been subtracted to produce a surface with variations of 1 meter or less, tantalizingly close to what we expect to see, and what we need.

Because the geoid estimate in Figure A is known to be imperfect, and is the cause of some of the problems in the Geosat topography map, we also need to use existing data in ways that are not dependent upon the gravity field. If we focus attention upon the time variability of

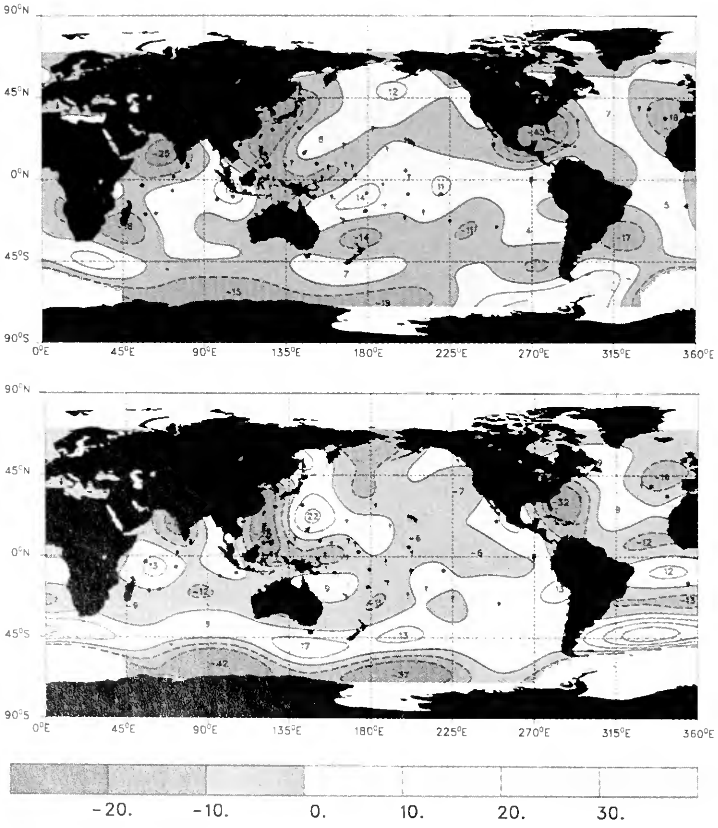


B. *This estimate, made from Geosat altimeter mission data of the actual shape of the sea surface, only shows the same long wavelengths as in the geoid at left. The similarity of these figures suggests the high accuracy of the existing altimetric technique. Ocean circulation appears to account for the very small differences between the two surfaces.*

oceanic circulation, then the change in elevation from one time to another can be obtained by subtraction, thus removing the geoid. Using Geosat data, the group that works with me at the Massachusetts Institute of Technology has been endeavoring to map oceanic variability at the very largest space scales. Global ocean-circulation deviation from its long-term average has been estimated over two successive three-month periods in late 1986 and early 1987. Geosat data results have been compared to, and then combined with, conventional tide-gauge measurements to produce these estimates. Estimates, averaged over three months (owing to the crude nature of Geosat data), depict ocean circulation movements that have hitherto been hidden from our instruments.

Ocean changes over a full year (November 1986 to November 1987) can be identified with altimetric measurements. Here almost all short spatial-scale fluctuations are removed. The most striking feature is the large low in the central Pacific Ocean. This drop in sea level is a clear manifestation of an El Niño that occurred during this period, which, from this vantage point, is evidently a global phenomenon. El Niño is an intense shift in the global climate system, manifested most prominently in the tropical Pacific area, in both ocean and atmosphere, and occurring irregularly every five to nine years (see El Niño, page 56).

Given this capability, a number of scientific problems, whose solutions would otherwise be pure speculation, become tractable. Although the most useful capability of satellite altimetric measurements lies in their ability to be used for global-scale estimates, they also provide a powerful new tool for studying problems of regional oceanography. By way of example, consider an area of 20° of latitude by 20° of longitude, that is, about 2,000 kilometers on a side. An oceanographic vessel can steam about 500 kilometers in a day if it does not stop to work. To map a region this size, allowing time for work, would typically take about three weeks, depending upon what sort of measurements were being made. By the time a ship had mapped the region, the flows depicted would have changed significantly—and it would be necessary to start all over again to build a picture of the temporal evolution (bear in mind that most US oceanographic cruises last no more than about a month). But with the altimeter measurement, we can compare what the ocean actually did with the predictions of a simple model of the region. Understanding the similarities and differences between these is the beginning of a new window on oceanic physics.



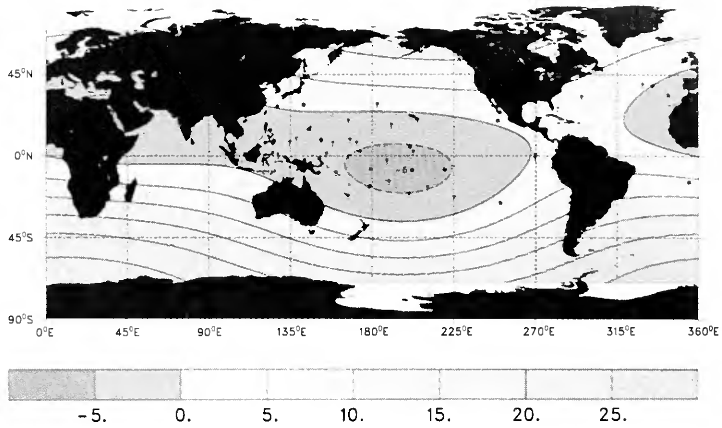
(Top) Time variation of the sea surface, at long wavelengths, for a three-month period beginning at the end of 1986, was obtained by combining Geosat altimetry with tide-gauge measurements (shown as black dots). The numbers are in centimeters. Some extreme values near Japan and the Gulf of Mexico should be disregarded because they are data processing artifacts. These pictures show oceanic motions that cannot be observed in any other fashion. (Bottom) The following three-month period was obtained in the same way.

What's Next in Satellite Altimetry?

Around the time this magazine reaches its readers, the US and France should be launching a spacecraft called TOPEX/POSEIDON. (The cumbersome name, a combination of ocean TOPography EXperiment and a French acronym, is mainly a tribute to bureaucratic and patriotic rivalries). This spacecraft's design and construction has been formally under way since 1980, and informal efforts extend at least five years before that. If successfully launched (by a French Ariane rocket) and if it operates according to specification, TOPEX/POSEIDON will be the first satellite designed and built for the central purpose of determining ocean circulation and its time variability from space.

In brief, TOPEX/POSEIDON carries a state-of-the-art, US-built radar altimeter with accuracy approaching 1 centimeter. It also carries an experimental French altimeter being tested for future missions. Several tracking systems are employed to overcome the difficult problem of determining the orbit radius. They include ground-based measurements that use lasers, a French system that relies upon having the spacecraft "talk" to some hundreds of passive transponders on the ground, and a system based upon the US Global Positioning System. Between these different systems, and the known dynamics of orbits, the required orbital accuracy should be achievable. Such precise tracking also greatly improves knowledge of the geoid. In addition, the spacecraft also carries special instrumentation to measure the electron and water-vapor content of the ionosphere and atmosphere.

With TOPEX/POSEIDON, we will be able to map the oceanic surface not at three-month intervals as shown in the two figures opposite, but probably at weekly intervals. Such maps will show a huge variety of flows and features that do not appear in our current maps owing to the high noise level in the underlying data. If all goes well, oceanography will finally have observations consistent with the global scale of the problem.



Changes in sea-surface elevation over a full year (November 1986 to November 1987) were estimated from Geosat altimetry and tide gauges. Only the very largest spatial scales are shown; the numbers are in centimeters. The big low in the middle of the Pacific Ocean is believed to indicate an El Niño.

Carl Wunsch is Cecil and Ida Green Professor of Physical Oceanography at Massachusetts Institute of Technology, where he has been a faculty member for many years. His present interests lie mainly in the problems of understanding global ocean circulation and its role in climate. He is one of the organizers of the World Ocean Circulation Experiment (WOCE), and is a principal investigator on the TOPEX/POSEIDON and ERS-1 altimetric spacecraft teams.

The Gulf Stream and Its Recirculations

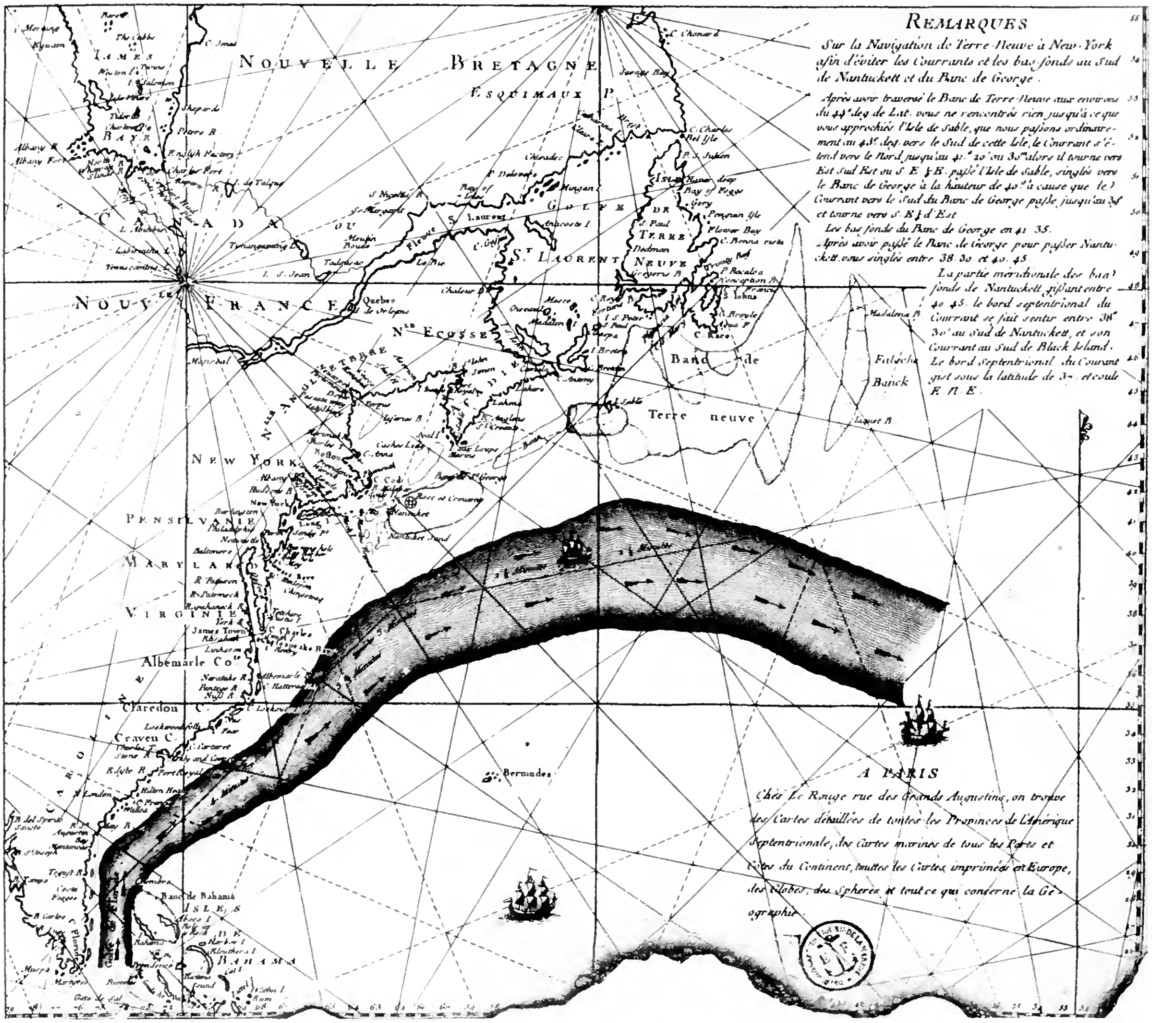
Nelson Hogg

The temperature contrast across the Stream, both in the air and in the sea, is obvious to anyone who makes the traverse.

Arguably the most startling nautical discovery that the early explorers of the new world made some 500 years ago was the swift, warm river of water off the coast of North America. Later called the Gulf Stream, this strongest of ocean circulation features has played an important role in the development of oceanography as a science, and has dominated scientific life at oceanographic institutions along the eastern seaboard. We have learned much, mostly of a descriptive nature, and several important intellectual leaps have been made, but a number of fundamental mysteries remain.

After its discovery, sailors quickly learned to exploit the Gulf Stream's swift current for quick return to Europe (or, more recently, to give a boost while racing to Bermuda). The obvious commercial aspect as well as the phenomenon's novelty stimulated considerable scientific speculation and experimental observation, a history of which is nicely summarized in the introductory chapter of Henry Stommel's book *The Gulf Stream*. Although many ship captains knew about the Gulf Stream, there were those who did not. The mail packets from England in the 18th century were notable exceptions, taking some two weeks longer to make the transatlantic trip than did merchant ships. The postmaster general at the time, Benjamin Franklin, discussed the problem with Timothy Folger, a Nantucket whaling captain. In his pursuit of whales (which were found to congregate on either side of the Stream) Folger often came across these mail boats "stemming a current that was against them to the value of three miles an hour and advised them to cross it, but they were not to be councelled [sic] by simple American fishermen." In an attempt to educate these captains, Franklin had a chart of the Stream produced from information given him by Folger.

In these early days, measurement technology was quite crude and one has to wonder how, well out of sight of land, the captains were able to determine the Stream's strength. The temperature contrast across the Stream, both in the air and in the sea, is obvious to anyone who makes the traverse, and the direct link between the surface-temperature front and the strong currents must have been quickly appreciated by the early



Watercolored by E Paul Oberlander/WHOI Graphics

Postmaster general Benjamin Franklin prepared this chart in 1769 in an attempt to educate the captains of the Atlantic mail boats about the Gulf Stream. Franklin obtained the information for the chart from Nantucket whaling captain Timothy Folger, who had observed mail packets "stemming a current that was against them to the value of three miles an hour...."

navigators, although it was not recorded until the 17th century. Surface thermometers were in use by the late 18th century, and they lead to the discovery of cold-water patches within the Stream (now called cold rings) and also of a branch of the Stream that continues north past Scandinavia (now called the North Atlantic Current).

Systematic study of the Gulf Stream began in the 19th century by Matthew Fontaine Maury and A.D. Bache (Franklin's great-grandson) of the US Coast and Geodetic Survey. Fourteen full-depth temperature sections were occupied between Tortugas and Nantucket. Somewhat later John Elliot Pillsbury began directly measuring the currents by anchoring his ship and lowering a crude current meter. He is credited with showing that the Antilles Current is a Gulf Stream tributary, and that the meandering activity increases downstream.

By the early 20th century the relationship between the density and velocity fields was beginning to be understood, and the importance of salinity and temperature in determining density was recognized and being measured. As we live on a rotating Earth, the usual physical laws of motion (Newton's laws) must be modified to account for this moving frame of reference. This gives rise to the so-called Coriolis force, named after the 19th-century French physicist Gaspard Gustave de Coriolis. This force is proportional to current speed and acts at a right angle to current direction (to the right in the Northern Hemisphere and to the left in the Southern). For the Gulf Stream to continue in a more-or-less steady direction, as it does, the Coriolis force must be balanced by an opposing force of equal magnitude. This is supplied by horizontal pressure changes in the ocean resulting from a small but significant sea-surface tilt (a 1-meter rise across the Gulf Stream) and internal density variations. This relationship, known to oceanographers as "the geostrophic balance," has enabled us to calculate current strengths from knowledge of the density structure alone. (It is not quite that simple; we also need to know the sea-surface slope, which has not been directly measurable until recently. But more on that later.) Usually an assumption is made about the velocity at some particular depth, most often that the velocity vanishes at some depth.

Henry Stommel provided the second important theoretical step. After World War II, Woods Hole Oceanographic Institution (WHOI) director Columbus Iselin asked Stommel why the Gulf Stream was where it was, along the western boundary of the ocean basin. Western boundary currents are a universal feature of the world's oceans and Stommel rose to the intellectual challenge. His explanation involved the principle of conservation of angular momentum on a rotating Earth, and the notion, accepted by then, that large-scale circulation is mainly driven by winds. In the subtropics, the westerlies to the north and the trades to the south tend to drive a large-scale, clockwise circulation. Stommel's crucial realization was that the angular momentum balance for water moving southward, away from Earth's axis of rotation, was fundamentally different from that moving northward. This introduces an asymmetry whose physical manifestation is the Gulf Stream.

The most ambitious attempt to map out the Gulf Stream was a coordinated survey by four ships in 1960.

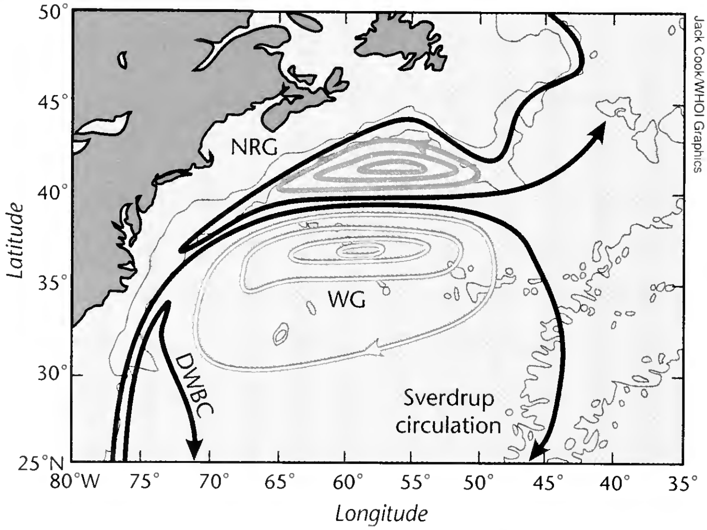
Armed with the geostrophic balance and the ability to measure temperature and salinity at various depths from surface to bottom, oceanographers have explored much of the world's oceans in the past 100 years and constructed elaborate schemes for large-scale circulation. The most ambitious attempt to map out the Gulf Stream was organized by Fritz Fuglister (WHOI) in 1960. This was a coordinated survey by four ships through the spring and summer of that year. For the first time it revealed in a clear way the Stream's large-scale meandering.

In calculating velocities from hydrographic data, Fuglister was somewhat uncertain about what to do regarding the reference-level problem. Conventional practice was to say that the velocity vanished at the bottom of the ocean; with this choice he calculated that some 70 million cubic meters of water was being transported eastward by the Stream every second in this region. (As a reference, the Mississippi carries about one-thousandth of this amount, and the Florida Current carries about 30 million cubic meters per second when it exits the Florida Straits.)

However, new instruments were being developed at this time that directly measured the water flow. One of these, the neutrally buoyant float (invented by John Swallow of the UK), could be ballasted to sink to a prescribed depth and, thereafter, be carried along with the water at that depth. Fuglister tracked some of these floats deep beneath the Stream for periods of a few days, and could clearly see that the zero-velocity assumption was suspect. Adjusting for this deep motion suggested to him that the Gulf Stream could be carrying at least twice the previously calculated amount.

The Gulf Stream '60 cruise was "synoptic" in oceanographer's terms: It occurred over a short period compared to the inherent time scale of the meandering phenomenon. Fuglister suggested that the geographic position of the 15°C isotherm at 200-meter depth was a good indicator of the Stream's northern edge. Donald Hansen (Atlantic Oceanographic and Meteorological Laboratories in Miami) then traced this position downstream of Cape Hatteras almost to the Grand Banks using a thermistor towed at that depth. Data from repeated tows over a year-long period beginning in the fall of 1965 revealed the full complexity of the meandering activity: Meanders grow as they propagate downstream from Cape Hatteras and can eventually pinch off to form detached pieces of the Stream. When this happens to the north, the detached pieces contain Sargasso Sea water in their centers and are called "warm rings." When it happens to the south, they surround cold continental slope water and are hence called "cold rings."

At this point, the basic descriptive work on the Stream was almost completed. All the major features but one had been documented. The remaining piece was the discovery of intense "recirculation gyres" to the north and south of the Stream. Those to the south were deduced by Val Worthington (WHOI) through a careful examination of water properties, as observed on a large number of sections across the Stream. Using a working hypothesis that parcels of water change little in their composition (their temperature, salinity, and dissolved-oxygen concentration) while moving, and knowing from Fuglister's earlier work that Gulf Stream eastward transport reaches a maximum between Hatteras and the Grand Banks, Worthington deduced that there must be at least one recirculating gyre to carry this transport back to the west. Direct measurement by current meters and neutrally buoyant floats in the region near the Stream has shown that there are actually two recirculations: one carrying water clockwise to the south, and the other carrying water counterclockwise to the north.



Jack Cook/WHOI Graphics

There are two recirculations in the Gulf Stream. One to the south carries water clockwise; the other to the north carries water counterclockwise. DWBC is the deep western boundary current, NRG is the northern recirculation gyre, and WG is the Worthington gyre.

Research on the Stream has intensified in the last decade through a program initiated by the Office of Naval Research (also supported by the National Science Foundation) called SYNOP (SYNoptic Ocean Prediction). The strong thermal contrast across the Stream combined with the meandering deflects sound in a way that creates "dead zones" where submarines can more easily escape detection. Being able to predict the Stream's path for periods of weeks in the future would clearly be advantageous, and the SYNOP program had the central goal of improving this predictive capability. Ultimately, this is a modeling activity, but we need improved knowledge of important dynamical processes to construct efficient and realistic models.

New technology has played a central role in the SYNOP program. The traditional shipboard hydrographic survey, the oceanographer's principal tool for so long, played second fiddle to a whole orchestra of instruments within SYNOP. Ship time has become very expensive and, at the same time, ships provide a clumsy tool for investigating a phenomenon with such strong spatial and temporal variability as the Gulf Stream.

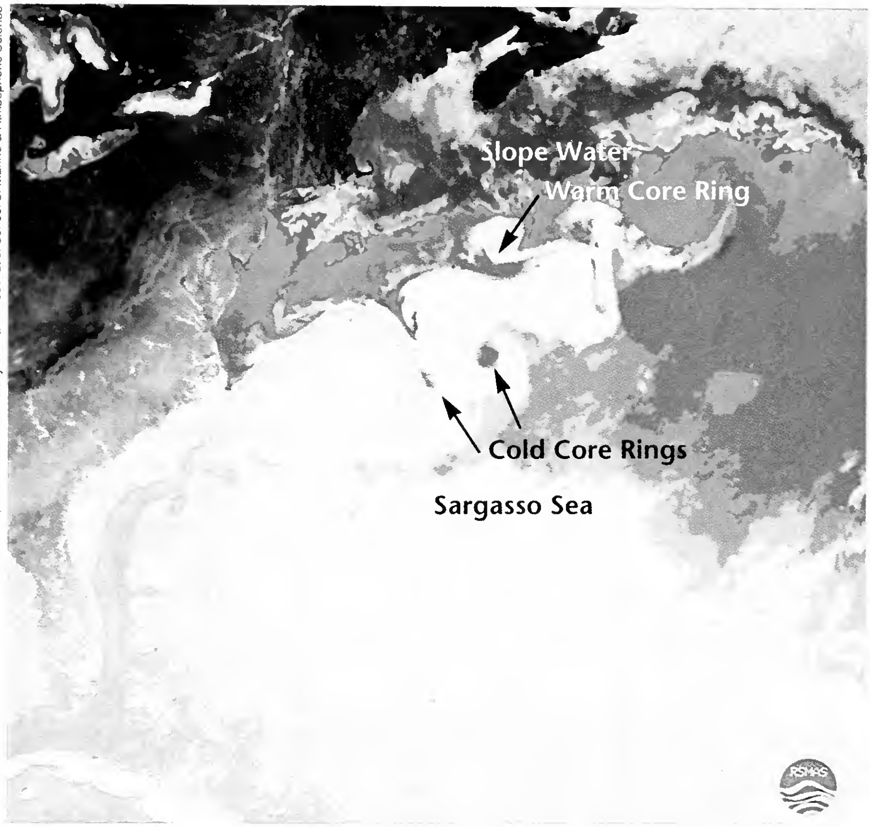
A modern variant of Swallow's neutrally buoyant float has been invented by Tom Rossby (University of Rhode Island). His RAFOS float (the name is the reversed spelling of the earlier SOFAR, or SOund Fixing And Ranging, float) receives acoustic signals from moored sound sources, and the time delay between transmission and reception is used to triangulate the position. In much of the ocean there exists an "acoustic duct" at about 1,000 meters depth where sound can travel several thousand kilometers without serious attenuation, and Rossby has been able to track these RAFOS floats from their deployment at Cape Hatteras to wherever they arrive a month or two later. At a predetermined time, the float drops a weight, surfaces, and then transmits its time-delay information via satellite to the user. The floats have provided new insight into fundamental dynamical balances in the meandering Stream, and the manner in which water parcels can be exchanged across the Stream.

Mooring technology, too, has evolved over the past 30 years from month-long deployments of uncertain success to reliable multi-year settings of large instrument arrays. The use of drag-reducing fairing on mooring wire and large, syntactic-foam buoyancy spheres in place of smaller glass spheres (the glass spheres have a larger drag for the same lift) have been particularly important to Gulf Stream work. Several arrays were set in SYNOP to measure the time-dependent Stream at critical locations from Hatteras to the Grand Banks. Besides the older current meters, new instruments included the inverted echo sounder (IES), which measures the time it takes for sound to travel from the ocean floor to the surface and back again. This measurement is proportional to the average temperature of the ocean above the instrument and, therefore, is sensitive to the Stream's relative position.

Nowhere else do satellites have so strong a signal to measure as in the Gulf Stream system.

A more complex acoustic instrument is the tomographic transceiver, which sends and receives sound from other transceivers. Variations in sound-arrival times are directly related to the average water temperature between the two instruments; the difference in time taken to go in one direction versus its reciprocal is a measure of the water's integrated horizontal velocity between the two moorings. From an array of such instruments, it is possible to reconstruct the thermal and velocity structure of the water between the moorings much as a radiologist can determine the internal structure of the body from a CAT scan. An array of eight transceivers was installed in the southern recirculation gyre by Carl Wunsch and Paula Rizzoli (Massachusetts Institute of Technology) and Yves Desaubies (France).

Satellites are continually increasing in importance in field experiments, and nowhere else do they have as strong a signal to measure as in the Gulf Stream system. Infrared sensors easily reveal the strong temperature contrasts between the slope water to the north and the Sargasso Sea to the south. Of particular importance is the existence of a sharp thermal boundary (or front) between these water masses along the Stream's northern edge. This is analogous to Fuglister's use of the position of the 15°C isotherm at 200 meters, and has been mapped over the past decades by Peter Cornillon and associates (University of Rhode



O. Brown, R. Evans, and M. Carle/University of Miami Rosenstiel School of Marine & Atmospheric Science

Ben Franklin provided a surprisingly good general map of the Gulf Stream in 1879. Today, satellite images, like this one for the first week in June 1984, offer colorful pictures of the Stream's complexities and its influence on the ocean basin. Warmer colors (reds, yellows) denote warmer waters; in this image the Stream is about 27°C. Meanders of the Stream pinch off to form eddies on both sides of the main flow. The lowest arrow indicates a counter-clockwise eddy that has recently formed south of the Gulf Stream, entraining in its core water colder than the surrounding Sargasso Sea. The upper arrow points to a clockwise "warm core" eddy. The rings move about the ocean basin independently for as long as two years before being reabsorbed by the Stream or dissipating.

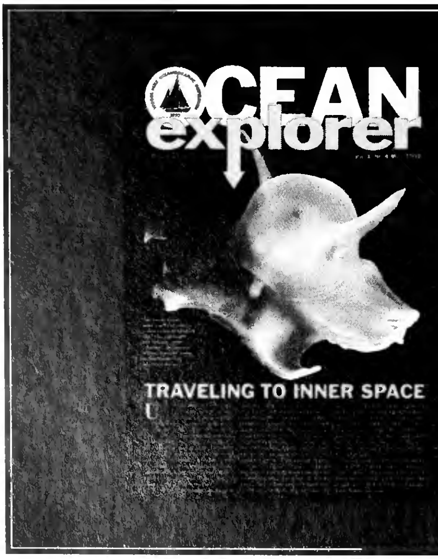
Island) to give the best available information on space-and-time scales of the meandering activity.

In the late 1970s, microwave sensors have been developed that measure sea-surface fluctuations of several centimeters averaged over several kilometers. Two satellites have been flown, the most recent being the US Navy's Geosat (See Observing Ocean Circulation from Space, page 9). As an approximately 1-meter change in sea-surface elevation exists across the Gulf Stream (again, due to the necessity of balancing the Coriolis force) these altimetric satellites are quite capable of observing Gulf Stream fluctuations, although not with the same spatial and temporal resolution of infrared instruments (because satellites see a spot on the ocean surface, while infrared instruments see the whole field of view).

The SYNOP field work has recently been completed, and scientific analysis is presently under way. It is too early to give many concrete results from the program; however, SYNOP does present a new way of doing business for physical oceanographers, and the ultimate scientific legacy is likely to result from close collaboration among observationalists, modelers, and theoreticians. A new and active area of modeling research involves "assimilating" data into the models to keep them on track as they evolve in time. This has been done for a number of years in atmospheric weather prediction, but only recently in the ocean spurred by the existence of real-time information from satellites and the development of instruments and mooring platforms that can transmit their information back to shore. In the long run, we anticipate that these models will allow us to fill, both in space and time, areas lacking in data, and then, by analyzing the adjusted models, obtain new insights into the ocean's workings. Even without the data-assimilation step, models have already become quite realistic in their representation of major circulation features, such as recirculations and statistics of how fluctuations are distributed about the mean state.

The last 500 years have yielded great advances in our knowledge of the Gulf Stream. What used to be a fuzzy river in the ocean is now a sharply focused picture. In it, the Gulf Stream is a frontal area between the warm Sargasso Sea and the cold shelf and slope waters that recirculate water back to the west. Many theoretical steps have been taken: We now realize why the Gulf Stream and its cousins (such as the Pacific's Kuroshio) in other regions exist along the western boundaries of their respective oceans, and we have some quantitative understanding of the Stream's strength. However, many mysteries remain. We still have no clear understanding of such important questions as, Why does the Stream separate from the coast at Cape Hatteras? or Why does the Stream meander? and Just why does water transport increase manyfold downstream of the Florida Straits? These questions have haunted physical oceanographers for generations, and are likely to continue for some time to come.

Nelson Hogg dreamt of being on warm, sunny beaches by the sea while growing up in northern Manitoba. It wasn't until he had a summer job during college at the Defense Research Establishment in Dartmouth, Nova Scotia, that he had that opportunity during an instrument-testing cruise to Bermuda. That was enough to convince him that oceanography had advantages over high-energy physics. For most of the time, since then, he has been a member of the Department of Physical Oceanography at Woods Hole Oceanographic Institution, most recently as a Senior Scientist.



A fund honoring the memory of *Henry Melson Stommel* has been established to endow the atlas collection of the MBL/WHOI Library.

Maps were one of Hank Stommel's abiding fascinations. He often sought out cartographers on foreign visits to add to his knowledge and his collection of maps. His interest in cartography and his appreciation of history came together in his 1984 book, *Lost Islands*, which details the appearance, disappearance, and reappearance of nonexistent islands on various maps.

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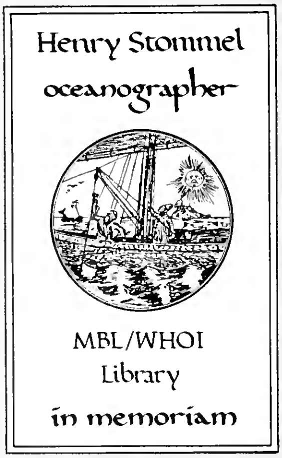
Henry Stommel
oceanographer

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in memoriam

This bookplate, featuring an image Henry Stommel often used on his own printing press, will be placed in volumes purchased with the endowment fund.

DEEP WESTERN BOUNDARY CURRENTS

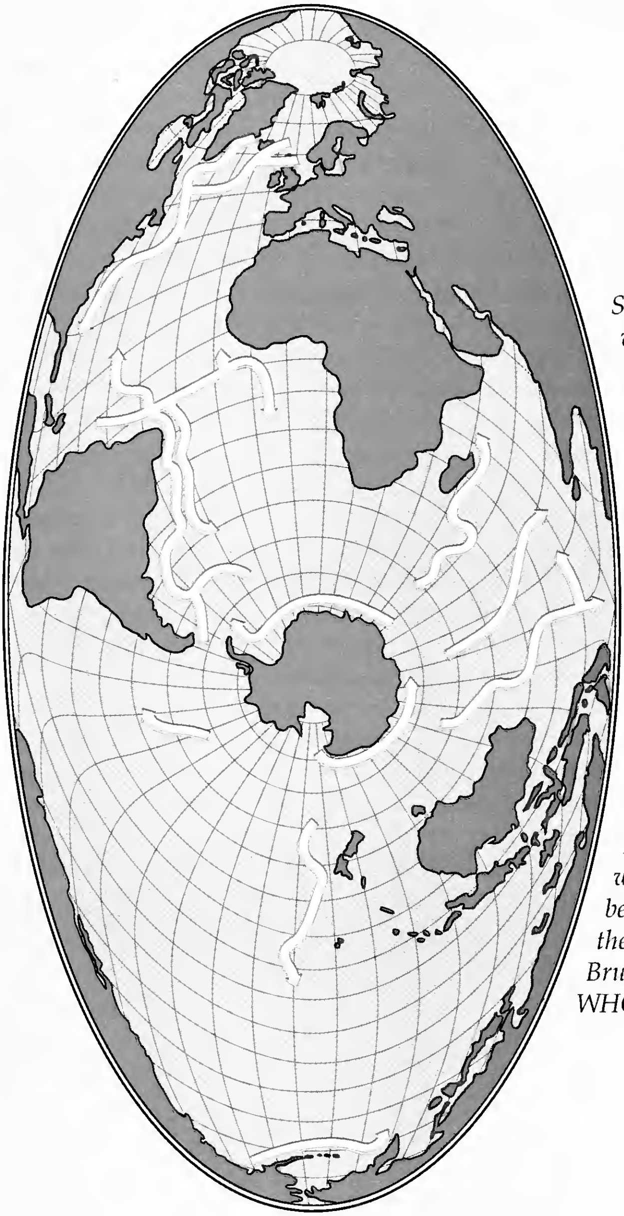
OCEANIC CIRCULATION is still a virgin territory where the unknown is waiting for us to find it. For young readers, this should be good news because there is a lot to be done. Large-scale deep currents driven by thermal forcing and freshwater flux have only been studied for the last 50 years or so. Work by Henry Stommel (Woods Hole Oceanographic Institution, WHOI) and others has revolutionized the way we look at ocean circulation today.

After deep water is formed in the polar oceans, it moves toward the equator to complete the thermohaline circulation loop. However, the path of this movement is not obvious. Scientists thought for some time that deep water should flow equatorward basinwide, but about the mid-1950s a different picture began to emerge. Stommel proposed a dramatically different scenario in which the ocean's interior deep water moved back toward its source.

To understand Stommel's argument, we can think of the ocean in terms of a two-layer model, with an interface at the main thermocline (a zone of sharp temperature decline about 1 kilometer below the surface). Within the ocean interior, flow must satisfy a dynamic constraint called "conserving planetary vorticity." According to this constraint, as the water warms, the cold lower layer loses water through upwelling, which is equivalent to stretching, and should go poleward—toward the source; similarly the upper layer is compressed as it gains water from the lower layer and should move equatorward—away from the source. This is quite a bizarre corollary of an abstract theory. Since we know that cold deep water formed in polar regions somehow reaches low latitudes and is not moving basinwide as originally theorized, there must be some special regions where this constraint is either violated or breaks down. Theory and observations suggest that the western boundaries of basins are the places where the meridional circulation is completed.

To confirm this seemingly conflicting theory, Stommel and his colleagues conducted laboratory experiments that indicated deep water should, indeed, move toward its source. In 1957, John Swallow (National Institute of Oceanography, UK) and Valentine Worthington (Woods Hole Oceanographic Institution) took neutrally buoyant floats to sea to verify their theory that deep western boundary currents were an exception to the planetary-vorticity conserving rule. In what must be the best example of theory and observation combining to unravel the mystery of the oceans, they confirmed the existence of a southward deep western boundary current off the East Coast of the US: Beneath the warm northward-moving Gulf Stream, there is a southward deep western boundary current that carries cold and relatively fresh deep water formed in the Norwegian and Greenland seas. Deep western boundary currents, cold and rich in oxygen but low in other nutrients, have now been identified in all the major basins of the world ocean.

RUI XIN HUANG



So far, our understanding of deep-water formation is quite poor because deep water always forms under severely harsh weather conditions in the polar regions that are difficult to observe. After deep water forms, it must move toward its source to complete the meridional circulation. Theory and observations suggested that currents at western boundaries of basins carry deep water toward its source. In 1957, Swallow and Worthington confirmed a deep western boundary current off the US East Coast; since then, deep western boundary currents have been observed in all major basins of the world ocean. (Courtesy of Bruce Warren. Drawn by Jack Cook/ WHOI Graphics.)

Woods Hole Oceanographic Institution

Overflows

The Source of New Abyssal Ocean Waters

James F. Price

More than four-fifths of the water in the oceans can be said to have a polar origin, in the sense that the water was last at the sea surface in the polar or subpolar seas.

The first scientific investigations of abyssal ocean temperature began in the 18th century with makeshift sampling devices (sometimes just buckets with valved covers) that could be lowered on sounding lines. Temperature was measured with thermometers once the sample was retrieved from the ocean, and suffered inaccuracy due to leaking buckets and heat conduction. Nevertheless, these crude early measurements were sufficient to show that nearly all of the abyssal ocean (depths greater than about 1,500 meters) was filled with very cold water that could only come from the polar or subpolar seas. This was true even in the tropics. By comparison, the warm waters of the ocean are confined to the upper 1,000 meters and then only in tropical and subtropical latitudes. More than four-fifths of the water in the oceans can be said to have a polar origin, in the sense that the water was last at the sea surface in the polar or subpolar seas. This is one of the most fundamental properties of the ocean, and research to understand how this happens continues to be a major effort in physical oceanography.

Density Differences Drive "Thermohaline" Circulation

Density differences drive much of the ocean's circulation. The density variations are directly due to temperature (thermo) and salinity (haline) differences. The basic idea of this "thermohaline" circulation is extremely simple and intuitive: Water that is made cold or salty at the sea surface (by heat loss to the atmosphere or freshwater loss due to evaporation) becomes more dense and tends to sink toward the ocean bottom. The sinking water will displace lighter water, which will in turn flow back toward the region of cooling or evaporation as a surface current. Thus we expect that cold, dense waters from the poles will tend to flow away from their sources and be replaced by warmer surface waters from low latitudes. The result is an overturning circulation whose deepest extent will depend upon the density of the source water and how it mixes with oceanic water as it descends. Oceanographers sometimes distinguish three layers in the abyssal ocean that each have a separate source or sources in the thermohaline circulation:

- an intermediate layer from the lower thermocline (typically 700 meters) down to a depth of about 1,500 meters,

- a deep layer from 1,500 meters to near the bottom, and finally
- a bottom layer that is actually in contact with the seafloor.

When we mean to refer to all three layers at once, we will use the phrases "abyssal ocean" or "abyssal waters."

The thermohaline circulation is thought to be the main process that can renew or change the properties of abyssal ocean waters (geothermal heating is another possible mechanism, but appears to be considerably less vigorous). We know from a variety of paleological and chemical data that the temperature and salinity of the abyssal oceans can change; it was different during periods of glaciation just 12,000 years ago, and vastly different 50 million years ago when sea level and the continental configuration were probably also very different from what exists today. From these observations we can infer that the ocean's thermohaline circulation must have been quite different during these epochs, but we don't know whether this was a consequence of atmospheric climate change, or, instead, a contributing cause. To interpret the paleoclimate record, and to better forecast how climate may change in the future, we need to learn much more about the physics of ocean thermohaline circulation. Here we review just one aspect of this problem: What are the sources of new abyssal waters, and how does this new water flow into the abyssal ocean?

The thermohaline circulation is thought to be the main process that can renew or change the properties of abyssal ocean waters.

Only a Few Locations Produce New Abyssal Waters

By "new waters" we mean water recently modified by interaction with the atmosphere, and especially cooling or evaporation, as these make water denser. Gas exchange and other crucial chemical and biological changes also occur at an enhanced rate when water is in contact with the atmosphere. Over most of the world ocean, the net heat or water exchange over a full year is nearly balanced, so that the ocean neither gains nor loses a significant amount of heat or fresh water. There are only a few special locations where surface water may be made dense enough to become abyssal water. These regions are characterized by strong winter cooling or evaporation, and/or are partially confined by topography. The former process may occur over an open-ocean region on the western side of an ocean basin, where cold, dry air blows off the continents during winter. This occurs off of the US East Coast during winter, and produces the 18°C water of the western Sargasso Sea that descends to a depth of about 300 meters (still well within the thermocline). The same kind of phenomenon also occurs in the Labrador Sea, and in years with especially severe winters the late-winter water may become as cold as about 3.5°C and descend to depths of 1,000 meters or more. Labrador Sea water is thought to be one of two significant sources of new intermediate waters that directly enter the North Atlantic.

The other important source of new intermediate water to the North Atlantic is the Mediterranean Sea. The arid climate of the surrounding land mass causes intense evaporation that raises Mediterranean water salinity to values of 38.4 parts per thousand, compared with 36.4 parts per thousand in the eastern North Atlantic (see Water, Salt, Heat, and Wind in the Med, *Oceanus*, Spring 1990). Although Mediterranean water is fairly warm, about 13°C, its salinity is sufficient to make it dense enough to sink nearly to the bottom of the North Atlantic, if it could arrive there in a pure form. However, as this dense, salty water spills over the sill at Gibraltar, it mixes with a large volume of overlying, fresher, Atlantic Ocean water, and ends up being neutrally buoyant at a depth of about 1,100 meters, thus becoming an intermediate water mass.

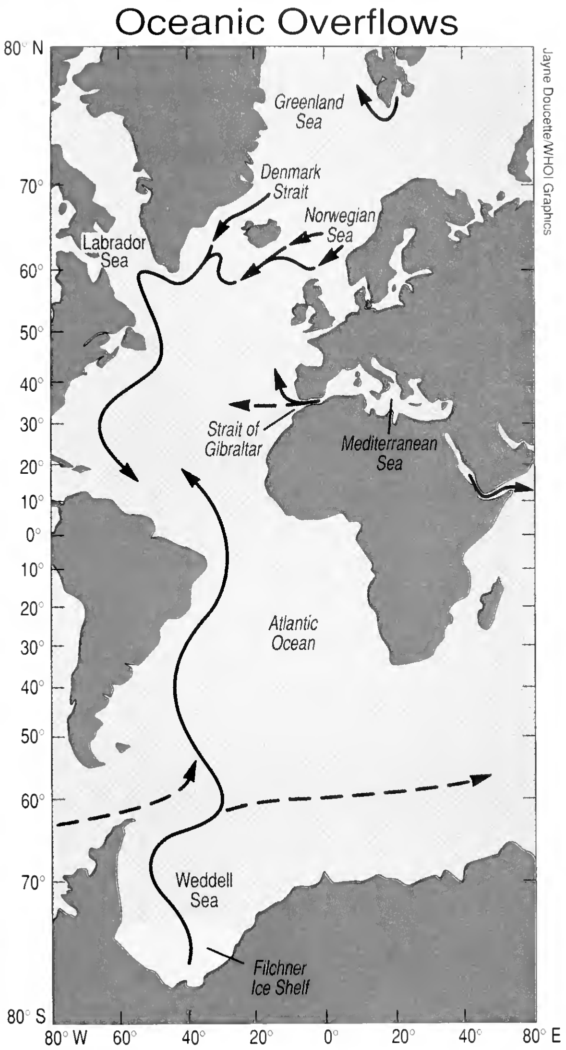
Since the earliest measurements were taken, it has been clear that deep and bottom waters must have polar origins; nevertheless, their exact source was not fully known until relatively recently, about the mid-1950s. By then seafloor topography could be drawn in greater detail, and the data base on the ocean's thermal and haline structure was just sufficient to reveal that deep and bottom waters in the North Atlantic have their main source in the Norwegian Sea. Winter cooling in those subpolar seas is, of course, intense; combined with ice formation, which leaves behind salt and thus increases the salinity in underlying seawater, it creates several types of very dense water. The densest water, called Norwegian Sea Deep Water, is produced on the surrounding continental shelves and perhaps in semi-enclosed bays. A slightly less-dense water type called Arctic Intermediate Water is produced in the central western Norwegian Sea basin. Together these two water types fill the basin, and enter the North Atlantic at two main sites. The Arctic Intermediate Water spills over the sill of the Denmark Strait, while the slightly denser Norwegian Sea Deep Water flows out mainly through the Faeroe Bank Channel south of the Faeroe Islands (and intermittently over the ridge between Iceland and the Faeroes). These are the only Northern Hemisphere sources of deep and bottom water to the world ocean.

Thermohaline circulation in the Norwegian and Mediterranean seas is in some respects a smaller-scale version of North Atlantic circulation.

The main Southern Hemisphere source of deep and bottom water is found around the Antarctic continent. Several sites may produce deep and bottom water, but the most important is thought to be the Filchner Ice Shelf on the continental shelf of the southern Weddell Sea. There water very near the freezing point, -2°C, called, appropriately enough, Ice Shelf Water, is produced nearly year-round. This water fills a depression in the shelf and then spills into the Weddell Sea.

All five abyssal-water sources noted above have one common feature: the water is produced by air-sea interaction over a semi-enclosed or marginal sea, rather than over the open ocean. An enclosed sea would seem to be favored for abyssal-water production for two reasons: An enclosed sea will likely have a more severe, continental (rather than marine) winter climate; and enclosed-sea waters are partially cut off from the horizontal circulation and large-scale stirring that occurs in the open ocean. Additionally, a shallow water column (for example, a continental shelf site) would also be favored because of its reduced heat capacity. Thus the densest waters for the world ocean are produced in marginal seas (Labrador and Weddell seas) or semi-enclosed seas (Norwegian and Mediterranean seas), and within the marginal seas themselves the densest water is produced in bays or on the continental shelf. Indeed, the broad pattern of thermohaline circulation within the Norwegian and Mediterranean seas is in some respects a smaller-scale version of the North Atlantic circulation as a whole.

In four of the five cases (all but the Labrador Sea) the "source" water fills the marginal sea up to the depth of the sill, which partially blocks exchange with the open ocean, and cascades over the sill as a dense bottom current. These dense currents are called overflows. From the perspective of the world ocean, the two overflows from the Norwegian



Jayne Doucette/WHOI Graphics

These are the four principal overflows that feed water into the abyssal Atlantic Ocean. The path of the Weddell Sea overflow may include a circuit around Antarctica before beginning a slow northward flow into the South Atlantic.

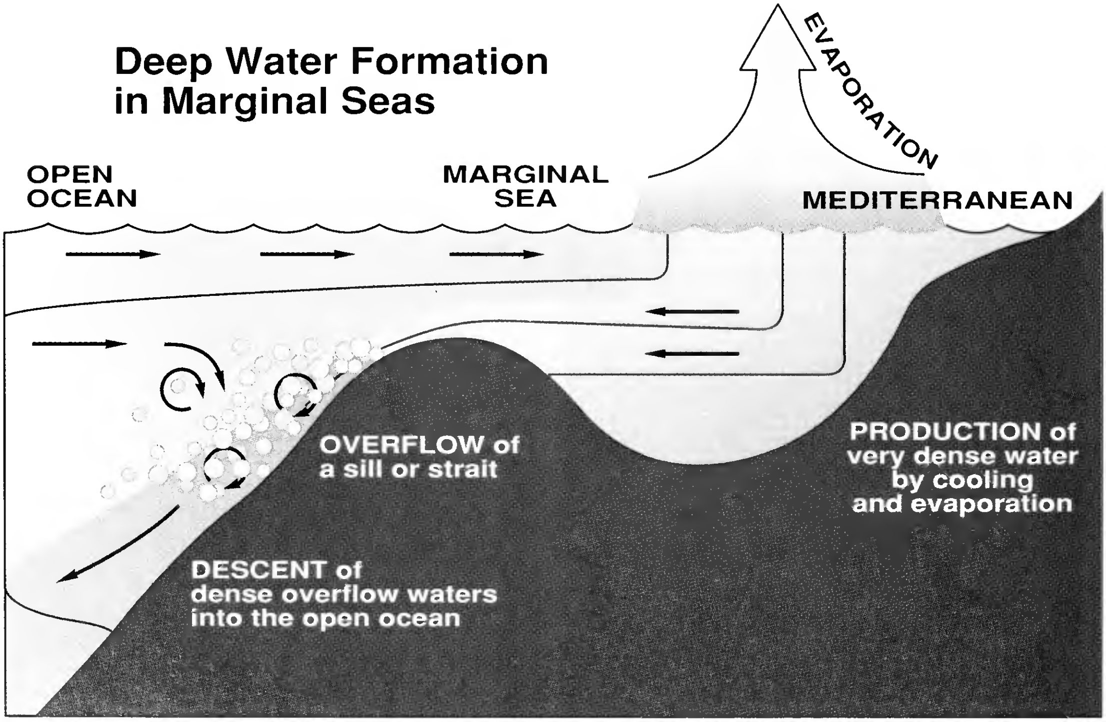
Sea and the overflow from the Filchner Shelf into the Weddell Sea are the main sources of new deep and bottom waters (there are other deep and bottom water production sites around the rim of the Antarctic, but there are none in the Pacific or Indian oceans), and the Mediterranean overflow is an important—but not the exclusive—source of North Atlantic intermediate waters.

The densest waters for the world ocean are produced in marginal or semi-enclosed seas.

Source Water and Mixing Create Abyssal Water

A striking and probably coincidental fact about source waters and resulting abyssal waters is that density ordering of the source waters is reversed in the final "product" water that eventually settles out in the open ocean. That is, if we list the source waters in order of increasing density at the sea surface (or just below the ice shelf) they go as follows:
- Filchner Shelf Water,
- Arctic Intermediate Water,
- Norwegian Sea Deep Water, and
- Mediterranean Water.

The latter is densest by virtue of its high salinity. After these source waters complete the overflow portion of their path to the deep sea, their density ordering is just reversed. Thus the lightest product water (which ends up at a depth of about 1,100 meters) is the mixed Mediterranean water; the next densest is the mixed Norwegian Sea Deep Water that overflows primarily through Faeroe Bank Channel; the next densest is the mixed Arctic Intermediate Water overflow through Denmark Strait (which together with the Faeroe Bank Channel overflow makes up most of the deep western boundary current); and finally, the densest of all is the mixed Filchner Shelf Water, which makes a major contribution to Antarctic Bottom Water. Common sense would lead us to expect the reverse ordering, with the densest source water ending up on the bottom, and so would any mixing process if it were uniform from case to case. However, it appears that the intensity of mixing, or at any rate the consequence of mixing, varies a great deal between these four overflows. (Also contributing to this reordering is the dependence of seawater density upon pressure. Specifically, the thermal expansion of seawater increases with pressure, so that warm waters, such as those from the Mediterranean, are less likely to reach the bottom than are colder waters.) To understand how this density reordering comes about, we must then understand something about the mixing process that modifies the source waters as they pass through the overflows.



Jayne Doucette/WHOI Graphics

Abyssal water production can be imagined to occur in three stages: First, intense cooling or evaporation acting over a semi-enclosed sea produces a very dense water type that fills the deep basin of the marginal sea. Second, this water must overflow the sill connecting the marginal sea with the open ocean. Third, the overflow must descend the continental shelf or slope before it can reach its final depth. During this descent the overflowing water may entrain a considerable quantity of lighter, overlying oceanic water, and thereby lose a substantial fraction of its density anomaly. This schematic is meant to represent the Mediterranean overflow, which settles out as an intermediate water mass. Other overflows that entrain less oceanic water go all the way to the deep seafloor.

Why Does Dense Source Water from the Mediterranean Overflow Produce an Intermediate Water Mass?

It is clear from historical data that the Mediterranean overflow loses much of its density because of strong mixing with overlying Atlantic water. We felt that the key to understanding the mixing effect on overflows was to first understand why mixing was especially intense in the Mediterranean overflow. The Mediterranean overflow is also a good place to begin an overflow study because it is more accessible than the subpolar overflows that may be partly covered by ice in some seasons, and because we have the results of a recent, successful study of exchange flow through the Strait of Gibraltar (the 1985 to 1986 Gibraltar Experiment led by Harry Bryden, WHOI, and Tom Kinder, now at the Office of Naval Research) that gave us a reference context for our overflow measurements.

Our field study took place in the fall of 1988 with a week-long cruise aboard R/V *Oceanus*, in collaboration with Tom Sanford (University of Washington), and Rolf Lueck (then at the Chesapeake Bay Institute, Johns Hopkins University). We were able to obtain current and density profile data from about 70 stations around and within the overflow of Mediterranean Water. These data revealed that most of the mixing between Mediterranean Water and the overlying Atlantic Water occurs within the first 40 kilometers west of Gibraltar where the overflow begins to descend the continental slope. In this region the current accelerates to speeds of more than 1 meter per second, and it appears that this rapid flow is what causes the mixing of Mediterranean and Atlantic waters. Farther downstream, the current slows to a relatively gentle flow of about 0.2 meters per second, and shows little sign of further mixing (salinity and density are nearly constant along the path). The now strongly mixed overflow water continues westward through the Gulf of Cadiz until it finally settles out at a depth of about 1,100 meters, where it is neutrally buoyant with respect to the surrounding North Atlantic water.

Based on this clear example, we can identify a similar pattern of localized strong mixing followed by long stretches of gentle flow without much mixing in the paths of the other overflows as well. In addition, it appears that the regions of mixing are those where the overflow currents are likely to be the strongest because of a steep bottom slope. It seems that if source waters from marginal seas are to make it to the ocean bottom, they had best go as slowly as possible to avoid mixing with overlying water. However, all of the overflows mix to some degree with overlying waters, entraining from 50 to 150 percent of their original volume transport in oceanic water, usually from depths close to the sill. Thus overflows not only carry new source waters into the abyssal ocean, but they also carry a substantial volume of thermocline waters that they entrain as they descend.

This and other recent work has given us fresh insight into the physics of these interesting and important overflow currents. To consolidate this new knowledge into a solid and functional form would seem to require at least two further, major steps. The first step might be another intensive field study of one or several specific overflows to verify that the dynamics of the Mediterranean overflow are indeed typical, as we suspect, or to add new elements to the conceptual model. An ongoing

If source waters from marginal seas are to make it to the ocean bottom, they had best go as slowly as possible to avoid mixing with overlying water.

study of the overflow into the Caribbean Sea by Bill Johns (University of Miami) may be just such a study. This overflow carries water from the deep western boundary current through Anegada passage and, unlike the nearly steady overflows from marginal seas that we emphasized here, appears to fluctuate on a several-week time scale. In that respect, the Anegada overflow may make a particularly good contrasting case study. The second step required to make this new knowledge of overflows functional is to learn how to represent overflows within the framework of numerical models that attempt to simulate the ocean's climate. The challenge here is to identify the essential, minimal elements of overflow physics that will allow the simulated overflows to vary realistically with changing hydrographic and topographic conditions. When we can do this with confidence, then we will have arrived at a truly useful understanding of this phenomenon.

James F. Price is an Associate Scientist in the Physical Oceanography Department of the Woods Hole Oceanographic Institution. His primary research interest is the dynamics of the upper ocean, and most recently that has included considering the ways in which the upper ocean can affect the deep ocean. He coaches junior soccer teams for his three children, and along with them enjoys fishing, biking, and flying.

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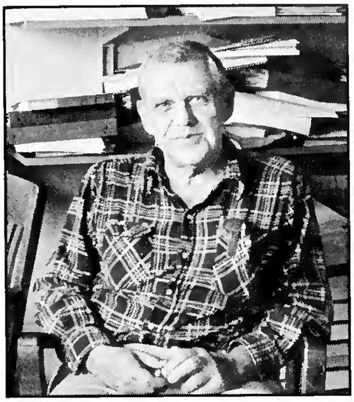

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FRESHWATER DRIVING FORCES...

OCEAN CIRCULATION is driven by wind stress and thermal forcing, and also by freshwater flux that results from precipitation and evaporation. In 1933, George R. Goldsbrough (University of Durham) first proposed that fresh water drives ocean circulation. His rather crude theory, which applied only to very idealized global patterns of precipitation and evaporation, has been neglected because it only predicted a small amount of vertically integrated water flux.

Salinity's role in ocean circulation has never been given much attention. Even the boundary conditions for salinity used in existing models are questionable. In fact, many models adopt a no-water-flux condition at the sea surface. To simulate the salinity change caused by evaporation and precipitation, an artificial salt flux has been introduced in these models. This might sound a bit crazy: Why on Earth is there a salt flux across the air-sea interface when there is no water flux? Why shouldn't we do it the other way around?

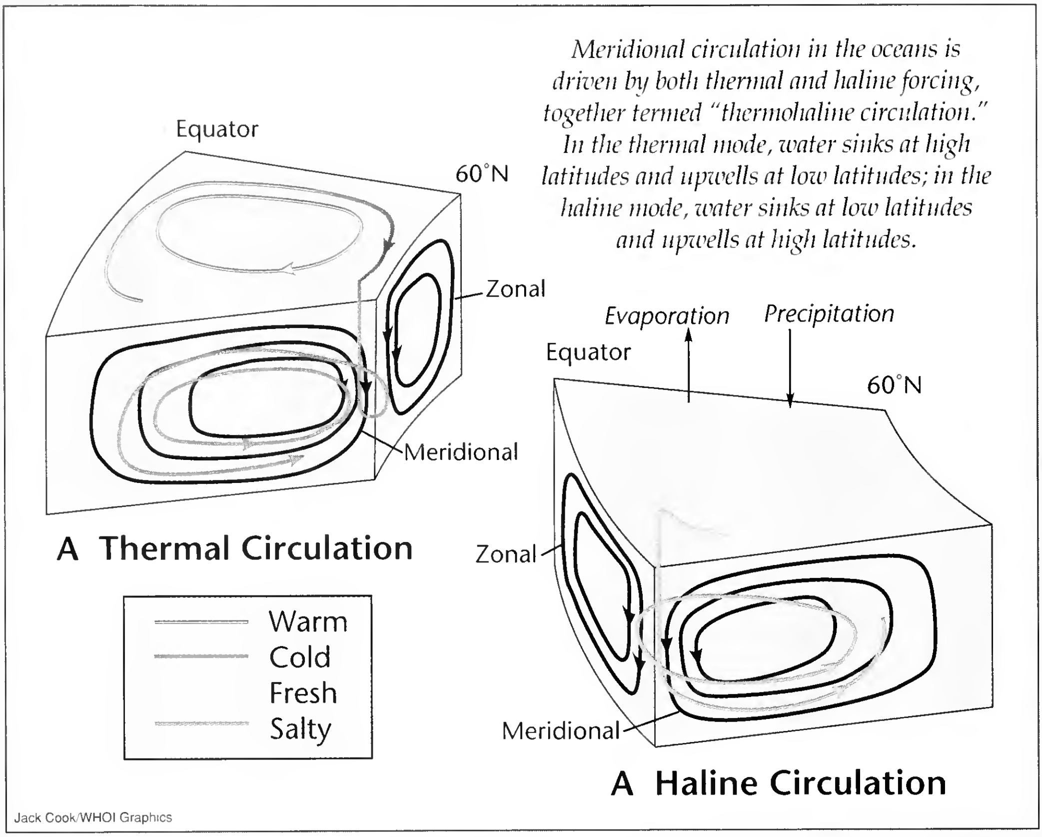
I've been pondering these questions over the past several years. Something about the way we deal with salinity isn't right, but what? And how do we do it correctly? Since early this year, I've been working on a numerical model with redefined boundary conditions: Fresh water passes through the upper surface, but there is no salt flux.

The trouble with the Goldsbrough theory is that it doesn't account for salinity. Were the oceans free of salt, the water flux associated with evaporation and precipitation would be truly negligible and the picture painted by Goldsbrough would be just right. However, oceanic salts change the picture entirely. In a salty ocean, evaporation at low latitudes makes water saltier and heavier, and precipitation at high latitudes makes water fresher and lighter. Consequently, the sea surface is higher at high latitudes than it is at low latitudes, and surface water flows equatorward where it becomes salty (due to evaporation) and sinks to the bottom. (Earth's rotation complicates the matter by modifying the circulation and introducing west-east asymmetry.) Thus, evaporation and precipitation drive a meridional circulation opposite to that driven by heat flux. However, such a three-dimensional picture associated with the freshwater flux has, to date, been ignored.

A simple model might illustrate the idea of evaporation- and precipitation-driven circulation. Let's assume that the only forcing is 1 meter per year of precipitation in the subpolar basin, and the same amount of evaporation in the subtropical basin. The total amount of freshwater flux is very small, but it drives a meridional circulation in the basin that has a mass flux several hundred times larger than the driving force itself. The periodic oscillation, periodic doubling, and chaotic behavior, depending on the parameters used, indicate that ocean circulation is not a steady-state system.

RUI XIN HUANG

...A New Look at an Old Theory



Meridional circulation in the oceans is driven by both thermal and haline forcing, together termed "thermohaline circulation." In the thermal mode, water sinks at high latitudes and upwells at low latitudes; in the haline mode, water sinks at low latitudes and upwells at high latitudes.

Jack Cook/WHOI Graphics

In a way, the entire North Atlantic ocean can be thought of as a big estuary. Freshwater input at high latitudes works like the fresh water from rivers. If there were no vertical mixing, all we would see is a very thin layer of fresh water being poured over the subpolar basin to flow toward the equator where it would evaporate. If the water were mixed vertically, the equatorward flow would carry some salt, and to maintain the salt balance locally, a subsurface return flow would appear. Thus, vertical mixing gives rise to a meridional overturning cell whose strength depends critically on the vertical mixing.

As I write this article, numerical experiments on the new model are being run on a CRAY-YMP supercomputer at Princeton University. These experiments are revealing many new phenomena relating to freshwater-driven circulation that will take some hard thinking to explain. All I can say now is that we will understand a lot more about freshwater-forced circulation five or ten years from now.

Mysteries of Planetary Plumbing

Raymond W. Schmitt, Jr.

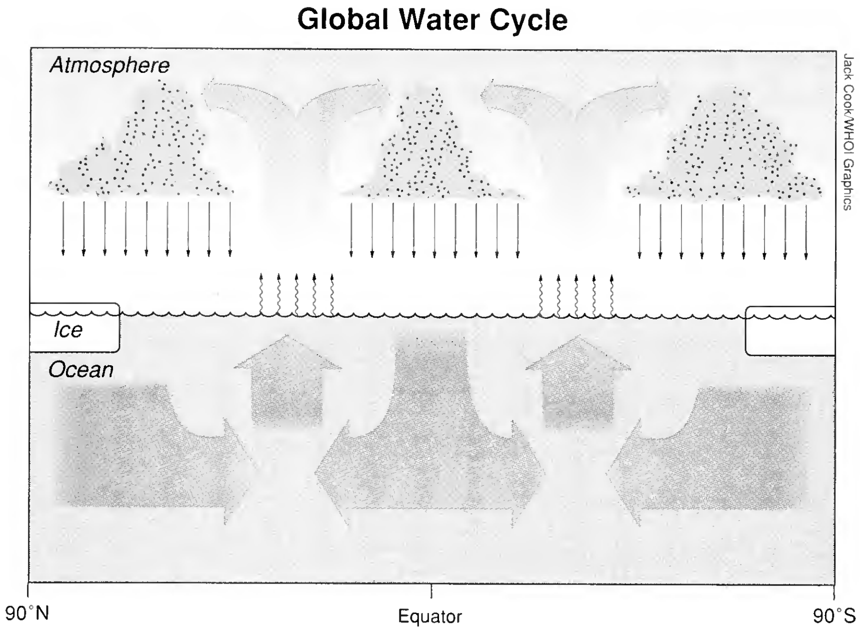
Some regard the hydrologic cycle as the premier problem in climate studies.

The hydrologic cycle is the process by which water is transformed through its phases (ice, water, and vapor) and transported around Earth by the ocean, atmosphere, and rivers. Past studies of the hydrologic cycle concentrated on the roles of the atmosphere and rivers, treating the ocean as a passive reservoir. (See *Oceanus,* Spring 1992, page 16 for a traditional diagram of this cycle.) However, less than 10 percent of the water transport (and a very small fraction of the total water) is involved in the terrestrial part of the water cycle. By far, the largest component (over 90 percent) involves only the exchange between ocean and atmosphere. As we begin to develop a more complete understanding of the global hydrologic cycle, the essential role of the dynamic oceans is beginning to emerge, yielding a very different picture of this cycle. A few basic facts point out their importance:

- The oceans represent the primary reservoir of water, containing 97 percent of Earth's supply; the atmosphere holds only 0.001 percent;
- nearly all the water rained out on land has evaporated from the surface of the ocean;
- water transport via ocean currents is hundreds to thousands of times larger than water transport via rivers; and
- most of the water carried by the atmosphere from one place to another on the globe is ultimately returned to its place of origin via the oceans.

However, we are remarkably ignorant about how the oceans fill their role in the global water cycle. Similarly, we know little about the impact of the hydrologic cycle on ocean circulation and climate. New data and insight into the "planetary plumbing problem" has revitalized interest in this long-neglected topic in oceanography. Indeed, some regard the hydrologic cycle as the premier problem in climate studies.

It is easy to see why this is so, even though most discussions of climate change emphasize the average global temperature as an indicator of the greenhouse effect. Increases of a few degrees in average temperature are predicted for temperate and polar latitudes. However, these rather small temperature changes are of less consequence to mankind than are the potential changes in rainfall distribution. We can use a bit more air-conditioning to get through future summer heat waves, but few localities are equipped to handle a radical change in the rainfall rate. Droughts in some areas, or torrential rains and flooding in others, will be far more important consequences of climate change than warming alone.



An oceanographer's view of the global water cycle. Ignoring the small portion of water transport associated with terrestrial processes, we focus on the 90 percent of the water cycle involved in ocean-atmosphere exchange. Water evaporated from the sea in middle latitudes is precipitated in equatorial and high-latitude rain bands. This requires broad, slow return flows in the ocean, which can be estimated from oceanographic data. Contrast this picture with the more traditional view of the hydrologic cycle given on page 16 of Oceanus, *Spring 1992.*

One has only to contrast the economic effects of the extended drought in California, or recent flooding in Texas, with the 1988 summer heat wave to appreciate the relative importance of temperature and water to humankind. In the last decade, a clear connection has been established between rainfall patterns over the US and surface temperature changes in the tropical Pacific associated with El Niño (see El Niño, page 56). Such shifts in the ocean-atmosphere system can have dramatic consequences for the terrestrial portion of the freshwater cycle and more recent evidence suggests that changes in the freshwater cycle can have significant consequences for the ocean as well. In particular, we believe that the intensity of the thermohaline circulation (see Overflows, page 28) is very sensitive to freshwater input.

Thermohaline Circulation is Sensitive to Freshwater Supply

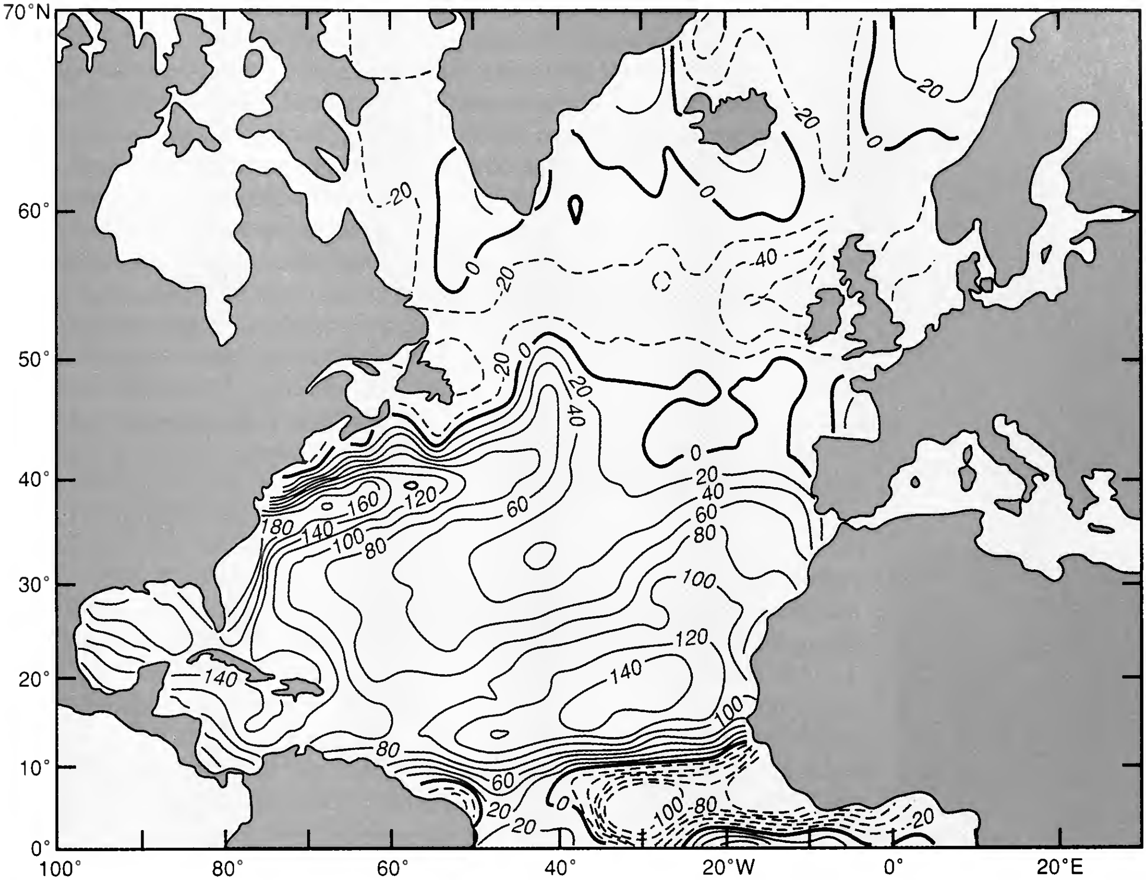
Thermohaline circulation is that part of the large-scale ocean flow driven by temperature and salinity variations, rather than wind. Temperature and salinity both affect the density of seawater. They are often nearly compensating in their effects on density, so that small changes in either heat or salt content can change the direction of ocean flows. In the Gulf Stream off Florida, recent studies by Bill Schmitz and Phil Richardson (Woods Hole Oceanographic Institution, WHOI) have attributed nearly half the flow to thermohaline circulation, and the rest to wind-driven circulation.

Thermohaline circulation depends on small density contrasts arising from differences in heat and salt content. The North Atlantic has a particularly large thermohaline flow, because there are regions near the Arctic where the water gets cold and salty enough to sink to the bottom. This cold, dense water must spread to the south as it accumulates in the basins of the Greenland, Iceland, and Norwegian seas. The southward bottom flow allows northward flow of warm, salty, surface water, which, when cooled, sinks and maintains the deep-water supply. Since the density differences driving this circulation are rather small, modest changes in the surface salinity caused by precipitation, ice melt, or river runoff can have large effects on circulation strength. Heat given up to the atmosphere by the cooling of these surface waters in the high-latitude North Atlantic is the primary reason that Europe experiences a much more moderate climate than other lands at that latitude. There is no significant thermohaline circulation in the North Pacific, where waters are too fresh to sink to the bottom. Nor, it appears, did this circulation always exist in the Atlantic. Paleoceanographers have developed a convincing case that a key feature of past Northern Hemisphere glaciations was the shutdown of the North Atlantic thermohaline circulation.

How could this occur? We have some fairly good notions about that question, thanks to an interesting experiment Nature performed some 10,000 to 12,000 years ago. It was a time of general warming, as Earth emerged from the last Ice Age. Global sea level was 100 meters lower than today, due to the large amount of water tied up in glaciers. The North Atlantic thermohaline circulation was growing stronger, and the heat it brought poleward helped to melt the ice. Great rivers poured water from melting glaciers into the sea; the Mississippi and St. Lawrence rivers carried many times more water than they do now. Then suddenly the warming trend reversed, and Europe plunged back into Ice Age conditions, even though winter sunshine levels continued to increase. From careful examination of the fossil shells of small marine animals and their isotopic composition, paleoceanographers have constructed a picture of ocean circulation changes that accompanied the so-called Younger Dryas event. Sea-level records from ancient coral reefs indicate that times of maximum melt-water discharge may coincide with ocean circulation changes. Models tell us that the deep sinking caused by cooling is extremely sensitive to freshwater inputs at the surface. That is, modest amounts of rain, runoff, or ice melt can dilute surface waters so that despite strong cooling, they are no longer able to sink. It seems that the melting glaciers provided enough fresh water to insulate the deep ocean from the atmosphere on a large scale, thus shutting off the North Atlantic thermohaline circulation and sending Europe back into Ice Age conditions.

Modest amounts of rain, runoff, or ice melt can dilute surface waters so that despite strong cooling, they are no longer able to sink.

Recently, oceanographers have documented a modern instance of freshwater capping in the North Atlantic. Salinity records from a variety of locations around the subpolar gyre suggest that a large discharge of arctic ice led to a patch of fresh upper-ocean water, which was circulated around the gyre during the 1960s and 1970s. When present in an area, the low-salinity surface water effectively stopped deep convection locally, thus affecting the temperature, salinity characteristics, and volumes of the subsurface water masses usually formed in the North Atlantic. Such features seem to be carried around the gyre on about a ten-year time scale. The insulating effect of such low-salinity caps causes reduced heat and moisture flux to the atmosphere, and cooler conditions on nearby land areas. Understanding such variability in both ocean and atmosphere on these decadal time scales is crucial for future climate prediction and understanding the greenhouse effect, since the expected warming could easily be hidden by such natural climate fluctuations. It will be a significant challenge, though, to sort out the complex climate response to high-latitude ocean freshwater input, and models are just beginning to attempt this.



Jack Cook/WHOI Graphics

The numbers within the contours are estimates for annual evaporation minus precipitation rates (in centimeters per year) in different North Atlantic regions. Obtaining accurate estimates of these rates is a challenge to oceanographers trying to better understand the global water cycle.

Measures of Evaporation, Precipitation, and Humidity Over the Sea are Elusive

One obstacle to our understanding of the global water cycle is a lack of knowledge of the evaporation and precipitation rates over the sea. Evaporation can only be estimated from the speed and humidity of the air, and such measurements are extremely scarce. Even when these variables are well measured, there is lingering uncertainty in the formula itself. Precipitation is even more problematic. Difficult to measure on land because of the effects of wind on rain gauges and the small spatial scales of its variability, it is virtually impossible to measure at sea with credible accuracy. Future satellites carrying rainfall-measuring radars and underwater acoustic sensors that detect the sound of rain on the ocean may someday provide us with a much better idea of precipitation at sea. For the moment, we must be content with empirical schemes that relate the weather observations of mariners to nearby coastal and island data in order to extrapolate across the ocean.

Phil Bogden (Massachusetts Institute of Technology), Clive Dorman (San Diego State University), and I generated maps of net evaporation minus precipitation for the North Atlantic using the work of the late Andrew Bunker (WHOI) and Dorman, which were derived from systematic calculations on millions of ship observations from the early 1940s to the early 1970s. These modern estimates provide much more detail in the patterns of evaporation and precipitation than does earlier work that depended on extrapolation from rather limited coast and island data. For instance, near the Gulf Stream off the east coast of the US, very large net evaporations are estimated. This area is characterized by especially deep surface-mixed layers in winter, which can only be generated by strong evaporative cooling. Similarly, the large gradients in evaporation minus precipitation in the tropics can help to explain the strong surface variability in salinity that is frequently observed there.

Thus new estimates are helping us to understand patterns of water-mass formation in different parts of the North Atlantic. They are also showing us that it is not only the high-latitude ocean that is sensitive to freshwater fluxes—indeed, we find that increased seawater density caused by surface evaporation is often as large or larger than the decrease in density caused by solar heating in low to mid latitudes. Clearly, we cannot afford to neglect the ocean freshwater cycle at any latitude.

In order to evaluate the uncertain available rainfall and evaporation data, WHOI/MIT Joint Program student Susan Wijffels and I have compared several compilations of evaporation minus precipitation for the North Atlantic. By summing estimates in different latitude bands it is possible to compute the expected net water transport in the North Atlantic. Because of the flow from the Pacific into the Arctic through Bering Strait, and runoff and precipitation in the Arctic itself, the net Atlantic flow is southward. However, if we contrast three currently available data sets we find that they differ by as much as 5 million cubic meters per second at the equator. This is over 2.5 times the flow of the Amazon River (by far the largest of all rivers) and 30 times the flow of the Mississippi! Thus, at the present time, uncertainties in the oceanic component of the hydrologic cycle far exceed the amplitude of the river component. It is ironic that the best-known portion of the hydrologic cycle and the one of most consequence for mankind—river flow—is actually a rather minor part of the global water cycle.

Clearly, we cannot afford to neglect the ocean freshwater cycle at any latitude.

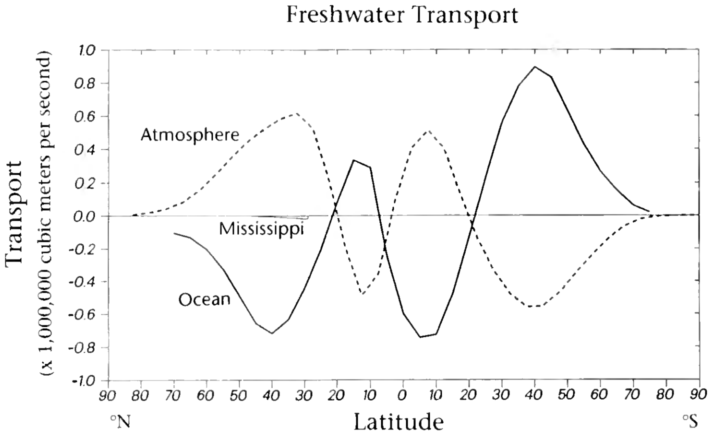
How Does the Saline Ocean Transport Fresh Water?

In our studies, we found a great deal of confusion in the scientific literature about how the saline ocean transports fresh water. Most regional studies invoke a reference salinity, and deviations away from that represent positive or negative freshwater anomalies. However, these cannot be extended to a global scale because there is no universal reference salinity. Indeed, the average salinity of the ocean must have varied with the changing ice volume during glacial periods. Sue Wijffels, Harry Bryden (WHOI), Anders Stigebrandt (University of Gothenburg, Sweden), and I have constructed a new scheme for ocean-water transport that recognizes that the fluxes of fresh water and salt between basins must be separately treated. We use actual measurements of transport through Bering Strait and estimates of rainfall, evaporation, and runoff to develop a picture of water transport in the North Pacific and Atlantic oceans. It contrasts dramatically with the previous scheme, which arbitrarily assumed no net water transport across the Atlantic equator.

The flow of water and salt from the Pacific to the Arctic and on to the Atlantic through Bering Strait is driven by a slight elevation of the Pacific relative to the other oceans. Estimated to be some 50 to 60 centimeters, it is caused by the lower salinity of the Pacific. The North Pacific is more diluted by rainfall than the Atlantic, where there is an excess of evaporation. Much of the extra water that rains on the Pacific is carried there by winds blowing it across Central America after it has evaporated from the surface of the Atlantic. We estimate that nearly all excess water falling on the North Pacific exits through Bering Strait, carrying with it a fair bit of salt. This salt must be resupplied by oceanic flows in the tropical Pacific that involve the northward flow of salty water and southward flow of fresher water, which amounts to no net flow. Similar mass-compensating flows are predicted for the South Atlantic, which must export the salt gained through Bering Strait but needs to export little water, because most of the surplus coming from the Pacific and high-latitude runoff and rainfall has evaporated by then.

Ocean Constraints on the Global Water Cycle

This appreciation of the separate nature of water and salt transports in the ocean is leading to new insight into the importance of ocean data in constraining the global hydrologic cycle. From east-west sections of temperature and salinity across an ocean basin, it is possible to estimate the salt and net water flows if the interbasin transport is known. For instance, if the flow of water through Bering Strait were not matched by southward water transport in the North Atlantic, North Atlantic sea level would rise by about 1 meter per year! If the salt transport were not also balanced, large differences in the salinity of the whole basin would appear in one decade.



The hydrologic cycle is rather steady, as there is no accumulation of water at any particular latitude. Freshwater transport in the ocean and atmosphere largely balance one another, and rivers (here we used the Mississippi as an example) typically contribute less than 10 percent to the cycle.

Since this is not happening, we can safely assume equality of salt flux, which in turn allows us to calculate the small net velocity of water across an east-west (zonal) hydrographic section, which is otherwise unobservable. A comparison of one such calculation at 24°N in the Atlantic with the summations of the surface-flux estimates is shown in the graph. It indicates that precipitation or runoff at higher latitudes is underestimated in current data sets. The recent estimates of flow rate and salinity in Bering Strait are "enabling measurements" that allow us to construct a picture of the global ocean hydrologic cycle from ocean data alone, thus avoiding reliance on uncertain surface-flux estimates.

However, until we collect many more zonal sections (a goal of WOCE, the World Ocean Circulation Experiment) that will permit such calculations, we must rely on currently available estimates of evaporation, precipitation, and runoff to develop a general picture of how the ocean transports fresh water. We have calculated the estimated water fluxes into and out of all the oceans as a function of latitude, in order to determine how much water they transport north or south. These estimated water fluxes are contrasted with the estimated transport of water (as vapor) in the atmosphere, derived from meteorological data, and the two estimates largely compensate one another. In general, the north-south transport by rivers would be less than 10 percent of transport by the ocean or atmosphere. That ocean and atmosphere largely balance one another indicates that the hydrologic cycle is steady; there is no accumulation of water at any particular latitude. It would be interesting to reach some understanding of the world water balance during the ice ages, since the buildup and decay of the glaciers involved such large quantities of water that the hydrologic cycle must have been significantly modified.

The Global Energy and Water Cycle Experiment (GEWEX) is being organized to improve understanding of the atmospheric and terrestrial branches of the hydrologic cycle later this decade. One component of GEWEX is a series of special satellites to observe rainfall over the tropics. These will be calibrated against ship, island, and buoy rainfall measurements. However, at present there are no formal plans for high-latitude satellite observations for precipitation, which would be of greatest consequence for climate studies. There is hope that improving meteorological models will produce realistic assessments of water fluxes in mid latitudes, but high-latitude regions will likely continue to be poorly sampled and poorly modeled for years to come.

Fresh water acts as both fuel for the atmospheric heat engine and a valve on the oceanic heat engine.

The Future

Faced with this situation, oceanographers are beginning to develop methods to measure surface salinity with greater regularity, since it is a good indicator of a climate's wetness or dryness. Along with temperature, knowing the salinity will allow us to know whether a water parcel is likely to sink, mix with underlying water, or stay at the surface, limiting air-sea exchange with deeper waters. There are now instruments that can measure salinity unattended for long periods; these need to be deployed on merchant ships, buoys, moorings, and autonomous vehicles to begin to develop an understanding of the time-and-space scales of surface salinity variations.

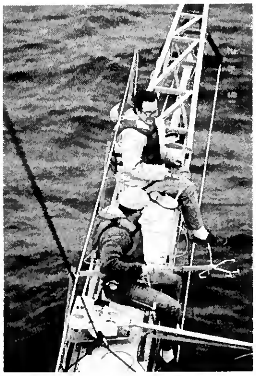
In addition, it is now clear that it is very important to measure the speed and salinity of the flows through straits, such as the one-way flow in the Bering and the two-layer flow at the Strait of Gibraltar. Such measurements would help determine important components of the hydrologic cycle and provide strong constraints on the extremely uncertain estimates of surface fluxes. Since they could be obtained with relatively modest resources and have significant implications for ocean climate, they should have high priority.

Similarly, zonal hydrographic sections provide useful checks on the water cycle as discussed earlier. Moreover, such data also allows us to compute the transport of heat by the ocean. Heat gained in the tropics is exported to the polar regions by motions in the atmosphere and ocean; in mid latitudes, atmosphere and ocean contributions to global heat transport are about equal. Much of the atmospheric heat flux is in the form of latent heat, because water is being carried as a vapor. The water-to-vapor phase change, which absorbs and releases great amounts of heat energy, is the fuel for many types of atmospheric motion. Most of the heat transport in the ocean is by the thermohaline circulation, in which warm water travels poleward near the surface and cold water returns equatorward near the bottom. The thermohaline circulation is very sensitive to freshwater fluxes. Thus, we have an interesting situation where fresh water acts as both fuel for the atmospheric heat engine and a valve on the oceanic heat engine. Because the ocean is the return conduit for water carried by the atmosphere, we can gauge the strength of both engines with ocean measurements alone. Since it is the complex interplay of these two engines that determines our climate, improving our understanding of the oceanic component of the hydrologic cycle must have high priority in future research efforts. The mysteries of the planetary plumbing system will undoubtedly challenge us for years to come.

Raymond W. Schmitt, Jr., is an Associate Scientist in the Department of Physical Oceanography at the Woods Hole Oceanographic Institution. He originally hails from southwestern Pennsylvania, where the flow of creeks and rivers inspired a youthful interest in fluid mechanics. He has made contributions to the study of small-scale mixing in the ocean—in particular the salt-fingering process, a double diffusive phenomena. His most memorable week at WHOI occurred in April 1988, when he learned that he had been awarded tenure and his wife Nancy Copley of the Biology Department was carrying twins. Life has not been the same since; he goes from double diffusion at work to double confusion at home!

Dynamics of the Ocean Mixed Layer

Robert A. Weller and David M. Farmer



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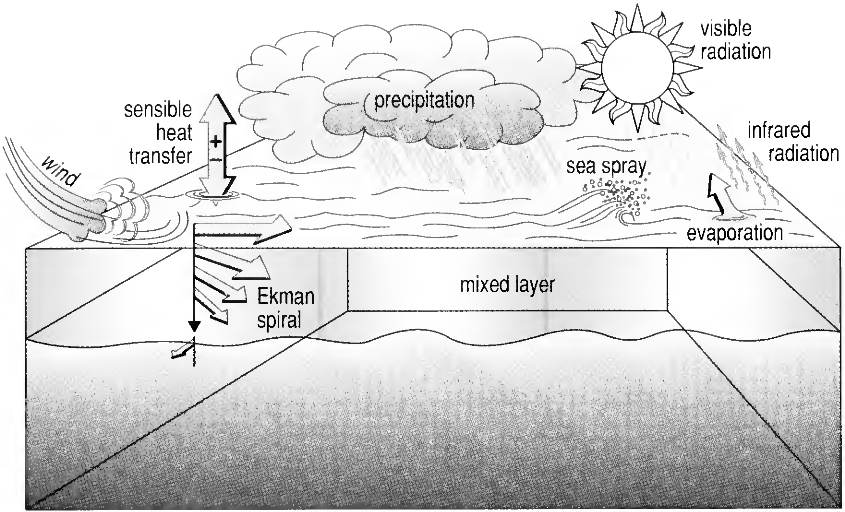
Bob Weller, in yellow slicker, and Rick Trask remove meteorological equipment from one of FLIP*'s booms at the end of a research period.*

Seawater is much denser than air and can store approximately 4,000 times more heat than the atmosphere. Further, over half the sunlight reaching the outside of Earth's atmosphere is absorbed by the ocean, while only 19 percent is absorbed by the atmosphere. Because air-sea heat exchange has a large effect on atmospheric circulation, the ocean could, based on its ability to store and transport heat, be the dominant partner in the coupled ocean-atmosphere system that determines global climate.

However, the entire water column is not often directly involved in air-sea interaction. A relatively shallow "mixed layer" isolates the ocean's interior from direct exposure to the atmosphere. This layer ranges from a few to several hundred meters in depth, is typically well mixed by wind and waves, and its temperature, salinity, and other properties are nearly constant with depth. Exchange of heat, carbon dioxide, fresh water, and other properties between the atmosphere and the large storage volume of the ocean's interior is thus controlled by the mixed layer and its dynamics.

Even so, the upper 3 meters of the ocean can store more heat than the entire atmosphere directly above it. By absorbing, transporting, and returning heat to the atmosphere at various locations over the 71 percent of Earth's surface that is occupied by ocean, the oceanic mixed layer influences both the weather and, on longer time scales, the climate. Perhaps the most well-known example of this is the El Niño-Southern Oscillation (ENSO), an eastward shift of warm mixed-layer water that is normally found at the equator in the western Pacific. ENSO results in dramatic weather changes in many parts of the world (see El Niño, page 56.) Less certain are the quantitative details of how and whether or not the mixed layer has begun to communicate atmospheric climatic change to the ocean's interior.

Understanding mixed-layer physical processes, including those associated with air-sea exchange and exchange between the mixed layer and the ocean's interior, is thus of special interest to physical oceanographers. In addition, multidisciplinary research in the upper ocean is common. The mixed layer is a region of significant biological and chemical variability, as well as the interface to the reservoir, source, and/or sink that the ocean's interior represents for greenhouse gases and many other chemical compounds. The physical dynamics of the mixed layer play an important role in biological and chemical variability and transport in the upper ocean.



Jayne Doucette and E Paul Oberlander/WHOI Graphics

These are the basic physical processes associated with mixed-layer dynamics. The layer is forced from above by the atmosphere. Heat from the atmosphere enters as sunlight and leaves as infrared radiation; heat is also lost during evaporation and by conduction. Fresh water enters the ocean as precipitation and leaves during evaporation, leaving salt behind at the surface. The wind creates surface waves and drives ocean currents. Mixing processes distribute the heat, fresh water, salt, and horizontal momentum from the wind within the mixed layer. They also can mix across the base of the layer, entraining fluid from below as the layer deepens. The Ekman spiral is discussed on page 49.

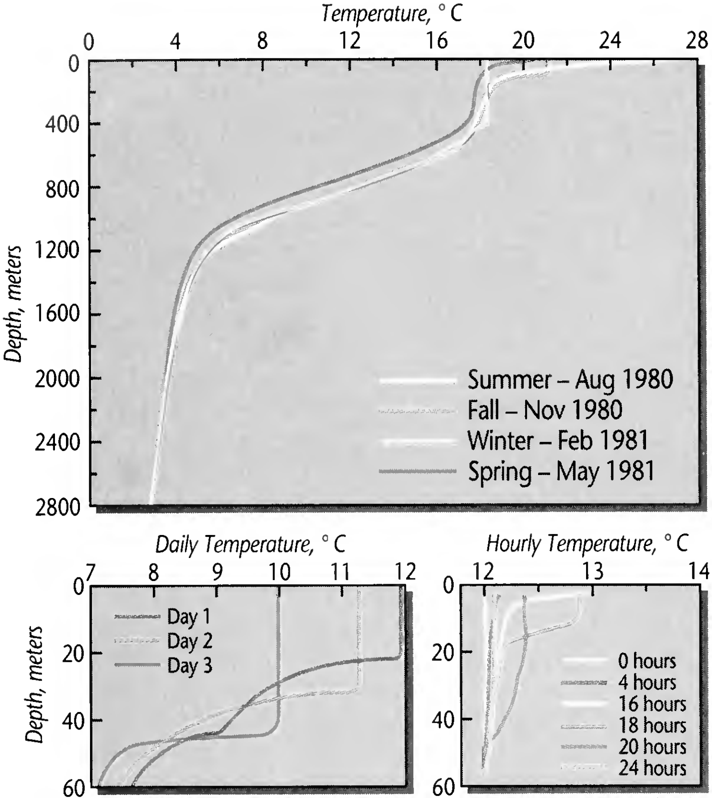
Studies of mixed-layer dynamics have three major goals:

- to understand how momentum, heat, and fresh water are exchanged between the ocean and the atmosphere at and near the sea surface;
- to understand how properties within the mixed layer—such as temperature, salinity, and horizontal velocity, whose magnitude and distribution are changed by atmospheric forcing—are mixed down from the surface and distributed both vertically and laterally through the mixed layer; and
- to understand the mechanisms for exchange between the mixed layer and the ocean's interior.

Physical Processes and Basic Mixed-Layer Dynamics

One of the most common observations oceanographers make is how water temperature varies with changing depth. Expendable temperature probes, known as XBTs or expendable bathythermographs, are routinely dropped from moving ships (merchantmen as well as Navy and research ships), and from some specially equipped aircraft, as a cost-effective method of collecting temperature profiles around the world. In general, summer temperature profiles show a shallow, warm mixed layer, and winter profiles show a deep, cool layer. Measurements taken hourly at one location reveal how the mixed layer changes with time. On a clear, calm day, the mixed layer becomes warmer and shallower as the sun rises and climbs high in the sky; then, in mid to late afternoon, it deepens and cools. In contrast, remaining on station and taking temperature profiles over one or more gray, windy days as a storm passes shows deepening and cooling of the mixed layer.

To some extent, we understand the physical processes responsible for determining the shape or vertical structure of temperature with depth, and we can relate changes in observed profiles to the time history of local atmospheric forcing. If either heat or moisture is added to the atmosphere at the air-sea interface, the air near the surface becomes less dense, rises, and leaves the interface. In contrast, input of either heat or fresh water at the sea surface makes the seawater less dense and, by increasing its gravitational stability, reinforces the tendency for that



Jayne Doucette/WHOI Graphics

Temperature profiles taken hourly (lower right), daily (lower left), and seasonally (top) reveal the movement of the mixed layer under different conditions. The hourly profile was taken from research platform FLIP *during a series of many warm days, ultimately creating a "summer" seasonal profile similar to the yellow tracing above. The daily profile was also taken from* FLIP, *but during a stormy period, when the cooling and deepening of the mixed layer produces a "winter" seasonal profile much like the blue line above.*

water to remain at the surface. Both the loss of heat and the residue of high-salinity water formed by evaporation make the surface water denser, causing it to sink beneath the mixed layer until it reaches fluid of matching density. Mixing can also play a role in modifying the temperature/depth profile. Wind waves mix the upper few meters of the ocean. If sufficiently strong, wind-driven surface currents can overturn a stable stratification, mixing and homogenizing the water. Such mixing at the base of the mixed layer entrains or stirs in cooler water from below, lowering the mean temperature of the mixed layer and also deepening it.

Heat exchange between the atmosphere and the mixed layer involves shortwave radiation (also called solar or visible radiation), longwave or infrared radiation, sensible heat flux, and latent or evaporative heat flux. Incoming solar (shortwave) radiation is partly (about 6 percent) reflected from the sea surface, and mostly absorbed in the upper few meters. The depth at which it is absorbed is determined by the frequency of the light and the optical properties of the water. The more energetic red component of sunlight has an extinction depth (where its intensity is 36 percent that at the surface) of approximately 3 meters, while the blue-green component has an extinction depth closer to 15 meters. The net longwave radiative flux is the sum of the infrared radiation that is emitted upward by the ocean surface and the infrared radiation coming downward from the sky.

Net longwave radiation is difficult to measure directly. We estimate net longwave flux using equations based on the knowledge that radiative flux from an ideal, a blackbody with emissivity of 1.0, is equal to the product of something called the Stefan-Boltzmann constant and the fourth power of the body's temperature. The calculations also make use of air temperature, emissivity of the sea surface (typically 0.96 to 0.98), cloud cover, and moisture content of the air near the surface.

Latent heat is the heat lost by the water at the sea surface during evaporation. The rate of evaporation and thus the latent heat flux depends on humidity and wind speed: The drier the air and the stronger the wind, the greater the evaporation.

Surface sensible heat flux is the heat lost from the sea surface to the air by conduction; it depends on the wind speed and the difference between sea-surface temperature and air temperature. Cold, strong winds blowing over a warm ocean result in large sensible heat flux.

Momentum is transferred largely through downwind, horizontal force at the surface, though some may be transferred just below the surface by the wave field. The momentum accelerates the water, resulting in wind-driven currents. Vertical mixing carries the horizontal momentum down into the mixed layer and accelerates the fluid below. Mixing is arrested when a strong vertical density gradient is encountered, and the base of the mixed layer is established at that depth. However, if wind-driven currents in the mixed layer are strong enough to cause shear flow instability (the shear is the difference in horizontal velocity, per unit of height), wavelike disturbances at the base of the mixed layer grow and overturn, deepening the base of the mixed layer, entraining fluid from below, and spreading the wind's momentum over the new, deeper layer.

Vertical mixing carries the horizontal momentum down into the mixed layer and accelerates the fluid below.

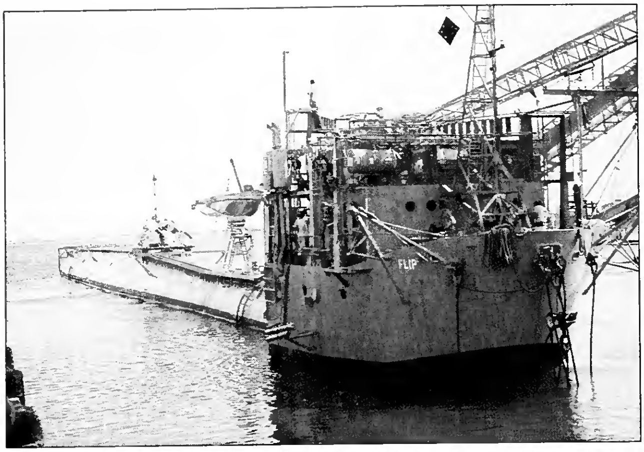
Testing a Theory: Ekman Dynamics

The early-1900s observation that Northern Hemisphere icebergs drift to the right of the wind led to the theoretical framework for predicting the vertical distribution of wind-driven currents in the mixed layer. Known as Ekman dynamics, after the Scandinavian oceanographer who proposed it, this theory includes the Coriolis force associated with Earth's rotation that is responsible for causing a moving body to turn to the right in the Northern Hemisphere. It did not include the effect of surface heating and cooling, but did include the assumption that horizontal momentum available at the surface from the wind was slowly mixed downward by small-scale turbulence within the ocean's mixed layer over a period comparable to or longer than the period of Earth's rotation. As a result, the current predicted by the Ekman equations both decays and rotates farther to the right with depth.

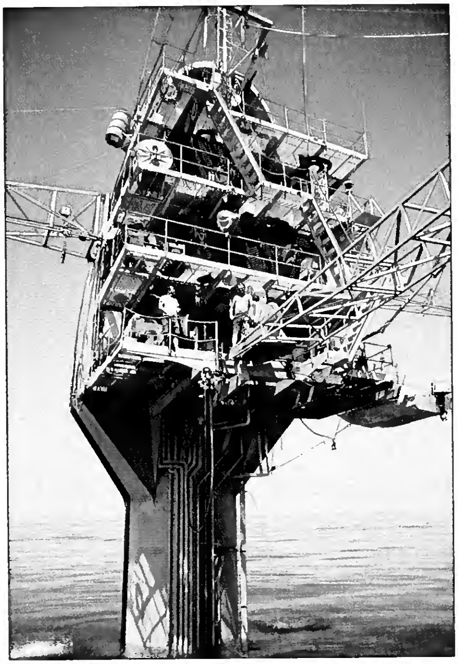
Over the years a number of field studies have been designed to observe an Ekman spiral in the mixed layer. The development of Vector Measuring Current Meters (VMCMs) facilitated these attempts. In 1983, working from the research platform *FLIP* (FLoating Instrument Platform, operated by the Scripps Institution of Oceanography), we collected a set of horizontal velocity, temperature, and salinity profiles, and a good record of mixed-layer surface forcing by air-sea fluxes. First used in 1978, the VMCM had been a part of several moorings as well as other uses on *FLIP* prior to this undertaking.

As the sun rose, incoming shortwave radiation warmed the upper few meters and a new, shallow, warm mixed layer formed above the old

Melora Park Samelson



Philip H. Rapp



Erika Francis

FLIP *(FLoating Instrument Platform), operated by the Scripps Institution of Oceanography, is towed to a research site in the horizontal position (above). At the site, ballast tanks are flooded with 1,500 tons of seawater to "flip" it to the vertical position (right).* FLIP *is outfitted with ingeniously designed hinged equipment that can be used with the vessel in either position. At far right, researchers aboard* FLIP *deploy (top to bottom) a real-time profiler, a vector-measuring current meter (VMCM), and a fluorometer.*

one. Within this new mixed layer, momentum inputs from changes in the wind's strength or direction could be seen clearly. Contrary to the predictions of Ekman dynamics, these new inputs of momentum were rapidly distributed downward, penetrating the whole of the new mixed layer within minutes. Vertical mixing was more rapid than Ekman suggested, and the wind-driven flow in the mixed layer was at any given time better described as a slab than as a spiral. The mean velocity profile that resulted from averaging over many cycles of the diurnal restratification was spiral-like, but the concentration of higher velocities near the surface did not result from slow vertical mixing but rather from the fact that shallow, warm layers had larger velocities.

By incorporating both surface heat flux and momentum and by including more efficient vertical mixing within the mixed layer, we developed a new model of the mixed layer. At any given time the predicted mixed-layer depth, the temperature structure of the upper ocean, and the mean wind-driven horizontal velocities of the mixed layer predicted by the model were much closer to the observations made from *FLIP* than those from an Ekman model. Since 1983, data sets from several other experiments have been analyzed and compared with predictions made by this model, and it is clear that both buoyancy and wind-stress forcing are essential components of mixed-layer dynamics.

Observations and a Better Understanding of Dynamics

Data collected from *FLIP* in 1983 and the resulting model both indicated that vertical mixing occurs rapidly within the mixed layer. However, neither the data analysis nor the model explicitly identify the physical process or processes responsible for the mixing. Thus, at that time, the lack of more detailed observations prevented progress toward a better understanding of mixed-layer dynamics.

The sea surface and upper part of the ocean are not easy locations for making the measurements needed to understand mixed-layer physics. Since wind stress on the sea surface is approximately proportional to the square of the wind speed, the rate at which the wind works on the ocean is proportional to the wind speed cubed. Thus, a few strong storms may have more profound effects on ocean properties than long periods of light winds. Moored surface buoys provide an important tool for research in the mixed layer, and our engineering efforts over the last decade to make oceanographic and meteorological instruments capable of surviving deployment on surface moorings have met with success.

The essential elements of mixed-layer dynamics are:

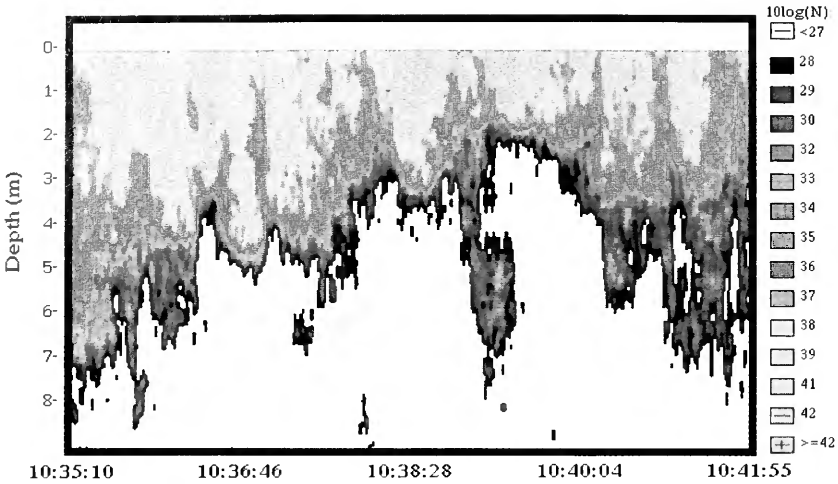
- air-sea fluxes,
- mixing processes that distribute the inputs of heat, fresh water, and momentum at or near the surface within the mixed layer, and
- processes capable of mixing across the base of the layer, deepening it, and entraining fluid from below.

Accurate surface-flux measurements have been a challenge. Sensors for wind velocity (speed and direction), barometric pressure, air temperature, sea-surface temperature, incoming shortwave radiation, incoming longwave radiation, relative humidity, and precipitation are mounted 3 meters above the sea surface and exposed to salt spray. While sensor improvements continue, careful choice of materials, such as Gore-Tex fabric as a spray shield around the humidity sensor, has in the past two to three years allowed us for the first time to frequently recover good data from all of these sensors.

Surface-wave velocities are large, while wind-driven currents are small.

Below-surface observation is equally challenging. Surface waves are always present when the wind blows, but we are just beginning to be able to observe their impact on the mixed layer. When waves grow large and break, the water that spills forward is driven below the surface. Surface water and air bubbles can be found at depths equal to several wave heights. It is important to determine whether these bubbles are organized into patterns, which would indicate the presence of a more systematic and coherent structure than small-scale turbulence. We now have available acoustic instruments like SUSY that can detect air bubbles, and they are expected to enhance studies of the vertical structure of horizontal currents within the mixed layer with data that would indicate how fast and by what means the horizontal momentum from the wind is mixed downward. (*Editor's Note:* We are told that SUSY is an acronym—but no one remembers what it stands for!)

Surface-wave velocities are large, up to hundreds of centimeters per second, while wind-driven currents are small, often ten centimeters per second or less. A velocity-measuring instrument or current meter for use in the mixed layer must accurately measure small, wind-driven flow even while experiencing the strong flow associated with surface waves



Date: 11/24/91

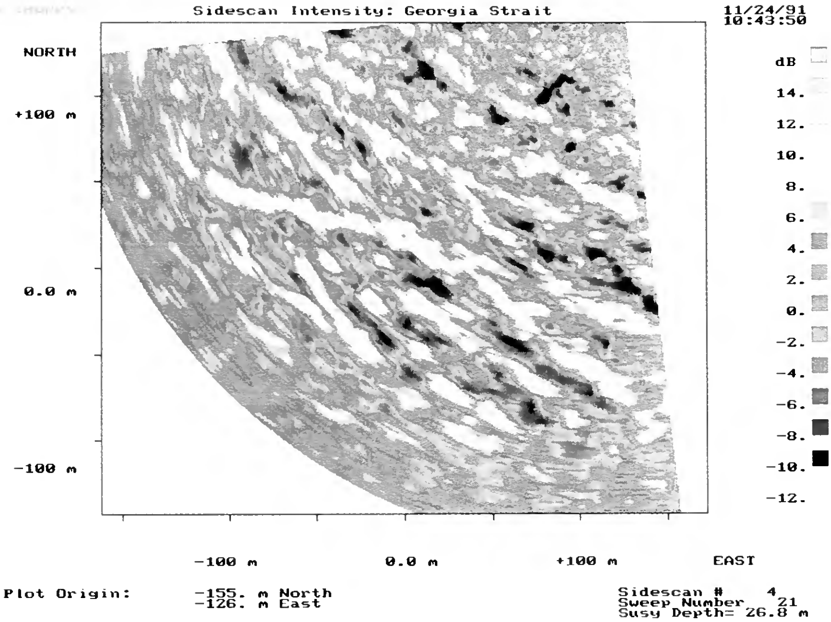
Farmer & Vagle

This acoustical backscatter intensity diagram, obtained from a vertical sonar, shows bubble clouds penetrating beneath the surface. This was taken at the same time as the scanning image on the facing page. The combination of these two different ways of looking at the ocean from beneath the surface provides useful insight into near-surface circulation patterns.

and the resulting motion of the platform to which it is attached. It must also be resistant to biofouling, mechanical wear, and corrosion. The VMCM was an initial step toward such instruments. Improved VMCMs can now be deployed in closely spaced vertical arrays from a stable platform such as *FLIP* or for up to one year beneath a surface buoy.

While the 1983 work from *FLIP* was exciting because it brought a step forward in modeling the mixed layer, it also presented the new challenge of discovering what physical process or processes accomplish the rapid vertical mixing observed. One possible process would be large, coherent eddies within the mixed layer whose axes of rotation were in the horizontal plane and which acted to carry surface fluid down and through the layer. The Nobel Prize-winning chemist, Irving Langmuir, had, when crossing the Atlantic Ocean in the 1930s, observed long, narrow lines of seaweed on the ocean surface that were parallel, some tens of meters apart, and aligned with the wind. Based on this observation and a subsequent set of experiments he conducted in Lake George, New York, Langmuir became convinced that there were pairs of counter-rotating eddies within the mixed layer aligned with their axes of rotation nearly parallel to the wind. Recent SUSY data shows that bubbles injected by breaking waves often align into long, narrow curtains, confirming the presence of eddies of the sort Langmuir proposed. This circulation is now known as Langmuir circulation, and each individual eddy is known as a Langmuir cell.

Breaking surface waves are not only an important mechanism for extracting energy from the wave field and making part of it available to the surface layer, but they also contribute to the flux of other properties across the air-sea interface. For example, wave-breaking entrains air, and thus plays a role in gas transfer between atmosphere and ocean. The majority of air in a whitecap quickly rises to the surface, leaving a small fraction in the form of microbubbles. The buoyancy of the smaller bubbles is insufficient to allow them to escape the Langmuir circulation, and they are drawn downward to depths at which the gas may go into solution. This so-called "wind-pumping" appears to be responsible for



Farmer & Trevorrow

This acoustically scanned image of bubble clouds was acquired with an azimuthally scanning sonar. The clouds are organized into somewhat irregular rows by the Langmuir circulation, and oriented approximately in the wind direction. Successive images of this type reveal much about the temporal evolution and merging of circulation cells.

supersaturation of oxygen and nitrogen, although not of carbon dioxide, in the surface layer of the wind-driven ocean. (Carbon dioxide, being reactive and much more soluble, appears not to be wind-pumped in this way; however, it is possible that the wave-breaking process alone may be more directly involved in carbon-dioxide transfer.)

Acoustic techniques appear to offer a number of interesting possibilities for studying processes near the ocean surface. Two general classes of acoustical measurement have proven especially fruitful in air-sea interaction studies: the use of high-frequency backscatter and the interpretation of ambient sound. High-frequency acoustical signals are readily scattered by microbubbles and can therefore be used to image the near-surface bubble population. An example obtained from one of the vertical sonars on SUSY is shown above at left. Bubble clouds penetrating more than 10 meters drift over the instrument. By using different acoustical frequencies it is also possible to determine the bubble size distribution. At the same time that the sonar collects bubble data, acoustical reflection from the sea surface gives wave elevation. Side-looking sonars simultaneously provide a horizontal view of the bubble clouds, and, in a recent development, they scan the surface to provide a two-dimensional view, shown above. The scanning image, also obtained with SUSY, shows bubble clouds organized by near-surface circulation into rows that are approximately aligned with the wind. Successive images of this kind provide striking views of temporarily evolving bubble-cloud formations that can yield insight into the dynamics of near-surface circulation.

Other measurements made from *FLIP* with VMCMs modified to measure vertical velocities found occasions of downward flow in excess of 20 centimeters per second in regions where flow between adjacent Langmuir cells converged. These measurements confirm that Langmuir circulation, when present, can provide a mechanism for very efficient vertical mixing.

At present, our limited observations show that the strength of Langmuir circulation can vary dramatically over the course of even one day. However, we lack the complete, long-running sets of observations needed to investigate both the reasons for that temporal variability and to quantify the impact of Langmuir circulation on the mixed layer.

Future Work in the Mixed Layer

Breaking waves are a prominent sound source, and an obvious target for acoustical observation.

Observations made with close vertical spacing in the upper tens of meters need to be accompanied by high-resolution measurements in the horizontal dimensions. Langmuir circulation is thought to include three-dimensional eddies ranging in size from a few meters in diameter up to a diameter close to the depth of the mixed layer. Initially, small cells appear. These do not disappear but are thought to feed energy to larger cells. In order to observe, understand, and, ideally, be able to predict these cells and their role in mixed-layer dynamics, techniques are needed to collect velocity, temperature, and salinity data in three dimensions and over time within the mixed layer. New, smaller current meters and acoustic sampling methods are being developed and will, we believe, provide the tools needed to further explore coherent flows within the mixed layer such as Langmuir circulation and other as-yet poorly understood aspects of mixed-layer dynamics.

The potential relationship between Langmuir circulation and waves, including breaking waves, needs to be examined more closely. Acoustical methods may be able to help here also. It has long been recognized that naturally occurring sound in the ocean is closely related to wind speed. The fact that most ocean ambient sound emanates from the sea surface suggests the possibility to exploit these signals for air-sea interaction process studies. Breaking waves are a prominent sound source, and an obvious target for acoustical observation. A small array of hydrophones can detect and track breaking events as they move above the array. Observations of this kind can be used to study the distribution and properties of wave breaking and their dependence on the wave field and meteorological conditions, including (we hope), potential relationships with Langmuir circulation.

Another technique that provides valuable insight into surface-layer circulation is direct measurement of the horizontal flow field using acoustical Doppler methods, in which the frequency of the acoustic echo is used to derive the velocity field. Rob Pinkel (Scripps Institution of Oceanography) and his colleagues in particular have demonstrated the power of this method for imaging ocean-surface circulation from *FLIP*. Pinkel's measurements clearly reveal the horizontal component of flow associated with Langmuir circulation over scales of hundreds of meters. Doppler processing of horizontal sonar data can also yield measurements of the nearly circular motion associated with surface waves; by using sonars pointing in more than one direction, it is possible to determine the directional wave spectrum.

Direct measurement of the relatively slow Langmuir circulation is also being studied by acoustically tracked neutrally buoyant floats. This new technique promises to provide observations of the tracks followed by individual water parcels as they circulate in the mixed layer, thus adding a three-dimensional picture to the point measurements and profiles obtained with moored sensors and other devices.

One of the benefits of developing a better understanding of mixed-layer dynamics will come when we include those dynamics in numerical models of the mixed layer. At present, forecast centers run sophisticated models of the atmosphere. At the same time, oceanographers have developed increasingly realistic models of interior-ocean circulation. Wind stress, heat, and freshwater flux from the atmospheric model are used to force the mixed layer of an ocean model. The resulting sea-surface temperature field is then used as the surface boundary condition for the atmospheric model. Persistent sea-surface temperature anomalies of 0.5°C in the North Pacific have been statistically correlated with weather change over North America. Sea-surface temperature anomalies of 3°C associated with El Niño are coupled with dramatic changes in global atmospheric circulation and regional climate variations. Models incorporating a better understanding of mixed-layer dynamics will improve our ability to predict mixed-layer temperature anomalies, and thus the ocean's impact on the atmosphere. Models of air-sea gas exchange and biological variability will also be improved.

The success of long-term surface moorings has also allowed us to expand our research on mixed-layer response to atmospheric forcing from one site to several, using horizontal arrays with spacings of tens to hundreds of kilometers. This is important, because it is the spatial variability on these scales in the atmospheric forcing, and the mixed layer's response to it, that couples, over the seasons, the ocean's interior to the atmosphere. As interest in climate change grows, so will the demand for improved understanding of how the mixed layer controls exchange between the atmosphere and the ocean's interior.

Oceanographers have developed increasingly realistic models of interior-ocean circulation.

Robert A. Weller is an Associate Scientist in the Department of Physical Oceanography at the Woods Hole Oceanographic Institution. A job with oceanographer D. James Baker, then at Harvard University, convinced him to change his undergraduate major from biochemistry to engineering and applied physics, and to pursue physical oceanography in graduate school and beyond. His primary interests are the physics of the upper ocean and atmosphere-ocean interaction. One or more months at sea each year provides the opportunity to pursue this work in the field and also to escape from telephone calls, memos, committee meetings, and other perils of work on land.

David M. Farmer was raised in England and studied at McGill University and the University of British Columbia, before joining the Institute of Ocean Sciences in Victoria, BC. Together with his students and colleagues he has studied lake dynamics, internal hydraulics, ice physics, and ocean-surface phenomena, most recently with emphasis on the application of acoustical methods.

El Niño

S. George Philander

"The sea is full of wonders, the land even more so. First of all the desert becomes a garden...."

When a group of experts met in Princeton, New Jersey, in October 1982 to discuss plans for an international program to study El Niño, they did not suspect that the most intense and devastating El Niño of the past century was even then forming in the Pacific Ocean. Less than a decade later, scientists were able to predict months in advance that El Niño conditions would develop toward the end of 1991. The phenomenon begins with relaxation of the usually intense westward trade winds that drive westward equatorial surface currents and expose cold water to the eastern Pacific surface. When the winds relax, warm surface waters that have been piled up in the western Pacific surge eastward.

As a result, during the early months of 1992 there were abnormally high sea-surface temperatures in the eastern tropical Pacific Ocean, coastal and equatorial upwelling ceased, and torrential rains fell. Even Texas and southern California suffered devastating floods.

Oceanographic Aspects of El Niño

The term El Niño originally referred to a warm, southward-flowing current that moderates low sea-surface temperatures off the coast of Ecuador and Peru during the early months of the calendar year, shortly after Christmas. (The Spanish term *El Niño* refers to the child Jesus.) Every few years the current is more intense than normal, penetrates unusually far south, is exceptionally warm, and is accompanied by very heavy rains. At first these years were known as *años de abundancia* (years of abundance) when

> *The sea is full of wonders, the land even more so. First of all the desert becomes a garden....The soil is soaked by the heavy downpour, and within weeks the whole country is covered by abundant pasture. The natural increase of flock is practically doubled and cotton can be grown in places where in others years vegetation seems impossible.*
>
> [R.C. Murphy, Oceanic and Climatic Phenomena Along the West Coast of South America During 1925. *Geographical Review*, 1926.]

At present, the term El Niño is not associated primarily with a joyous event, but with ecological and economic disasters. Because economic development, including fisheries that exploit the abundance of fish in the usually cold waters of Peru, are vulnerable to El Niño's climate changes, there is now a pejorative view of what once was a joyous occasion.

Not until the 1960s did oceanographers realize that the unusually warm surface waters off the coast of Peru during El Niño extend thousands of kilometers offshore, and are but one aspect of unusual conditions throughout the upper tropical Pacific Ocean. Tide-gauge data collected by Klaus Wyrtki (University of Hawaii) provided one of the first indications that El Niño is a consequence of changes in the winds that drive the ocean.

The lower panels of the figures on the following pages show schematically what happens in the ocean. During periods of intense trade winds, warm surface waters are piled up in the western tropical Pacific (so that sea level is high there) while cold water is exposed to the surface in the east. Surface currents at the equator are intense and westward during such periods. When the trade winds relax, as happens during El Niño, the warm surface waters in the west surge eastward so that isotherms shoal in the west and deepen in the east. The westward surface currents at the equator now weaken and often reverse direction, redistributing warm surface waters eastward. Details of this redistribution depend on the way in which the winds relax, and involves currents and oceanic waves that slosh back and forth across the Pacific. By studying the response of each of the three tropical oceans to seasonal wind changes—for example, the monsoons over the Indian Ocean—oceanographers have learned much about the processes controlling the ocean's adjustment to wind changes, and they have developed computer models that realistically simulate the oceanic response. If wind changes during a certain period are specified, then the models accurately reproduce El Niño conditions during that period. One of these models is now being used operationally at the National Meteorological Center in Washington, DC, to describe conditions in the tropical Pacific each month.

When the trade winds relax, warm surface waters in the west surge eastward.

The Southern Oscillation

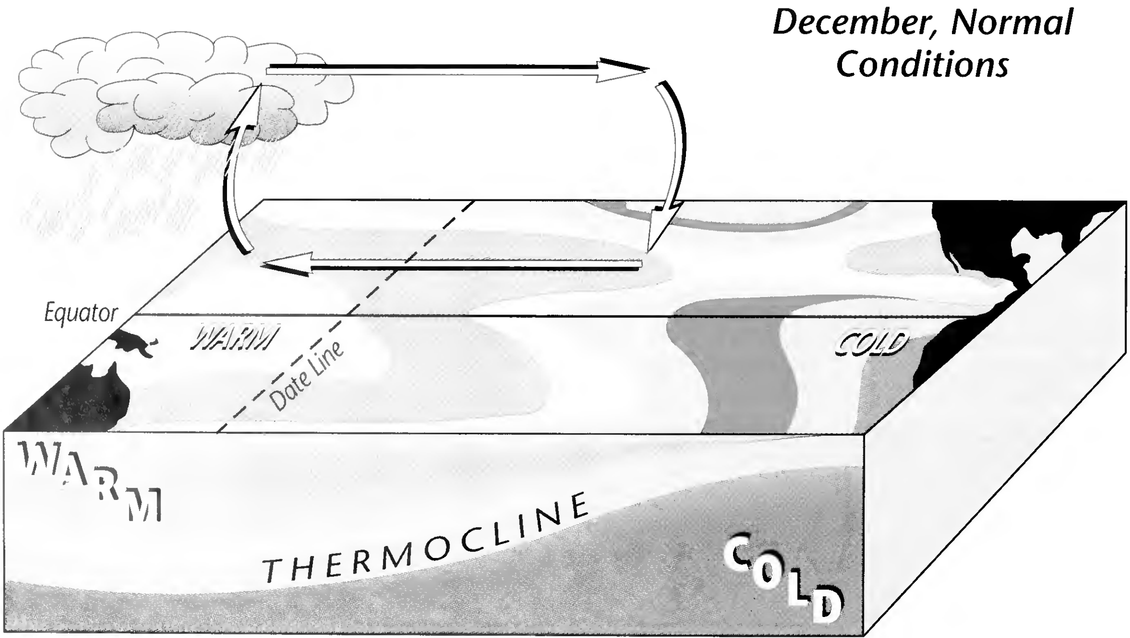
From an oceanographic point of view, El Niño is caused by changes in the surface winds over the tropical Pacific Ocean. But what causes the interannual (year-to-year) wind fluctuations? Efforts to describe these fluctuations, and, more generally, to document interannual circulation variations in the tropical and global atmosphere, started toward the end of the 19th century. Gilbert Walker, who became director-general of observations in India in 1904 (shortly after the famine of 1899 when the monsoons failed), initiated this research in an attempt to predict monsoon failures. He knew of evidence that interannual pressure fluctuations over the Indian Ocean and eastern tropical Pacific are out of phase: "When pressure is high in the Pacific Ocean it tends to be low in the Indian Ocean from Africa to Australia," he wrote.

This irregular interannual oscillation, which he named the Southern Oscillation, led Walker to believe that the monsoons are part of a global phenomenon. He set out to document the oscillation's full scope, in the hope that it held the key to monsoon prediction. Walker found that the Southern Oscillation is correlated with major changes in rainfall patterns and wind fields over the tropical Pacific and Indian oceans, and with temperature fluctuations in southeastern Africa, southwestern Canada, and the southern US. Attempts to translate these findings into monsoon predictions failed, and Walker's contemporaries expressed doubts about the statistical relations inferred from relatively short records. Many years later the analysis of much longer records resoundingly vindicated Walker.

The sea-surface temperature data available to Walker were inadequate to determine whether the ocean is involved in the Southern Oscillation. Confirmation that this is so came in 1957 and 1958, during the International Geophysical Year, when El Niño occurred. It was noted that unusually warm surface waters were not confined to the coast of South Africa, but extended far westward. This coincided with weak trade winds and heavy rainfall in the central equatorial Pacific, a normally arid region. Jacob Bjerknes (University of California, Los Angeles) proposed that the coincidence of unusual oceanographic and meteorological conditions is not unique to 1957 and 1958, but occurs interannually, and that El Niño is in fact one phase of the Southern Oscillation. (An apposite term for the complementary phase is La Niña.) Bjerknes furthermore proposed that, from a meteorological perspective, the interannual Southern Oscillation is caused by changes in sea-surface temperature. Over regions of high sea-surface temperatures (and high land temperatures) the air tends to rise so that low-level winds converge onto these areas. The winds carry moisture, evaporated from the ocean; when this moisture-laden air rises, condensation, clouds, and heavy precipitation result. During La Niña, the region of rising air is confined to the western tropical Pacific where sea-surface temperatures are high. During El Niño, the warm surface waters spread eastward and so does the region of heavy rainfall. Models of the atmosphere can now simulate the interannual Southern Oscillation between cold, dry La Niña and warm, wet El Niño, provided the interannually changing sea-surface temperature patterns are specified.

Atmosphere-Ocean Interactions

While oceanographers believe El Niño is caused by a relaxation of the trade winds, meteorologists attribute the change in the winds to the change in sea-surface temperatures. Bjerknes first realized that this



In a normal year, intense westward winds (white arrows) drive westward equatorial currents that push warm Pacific surface waters steadily to the west and expose colder waters, upwelling from the deeper water column, to the surface in the east. (After Verne Kausky, National Meteorological Center.)

Jayne Doucette/WHOI Graphics

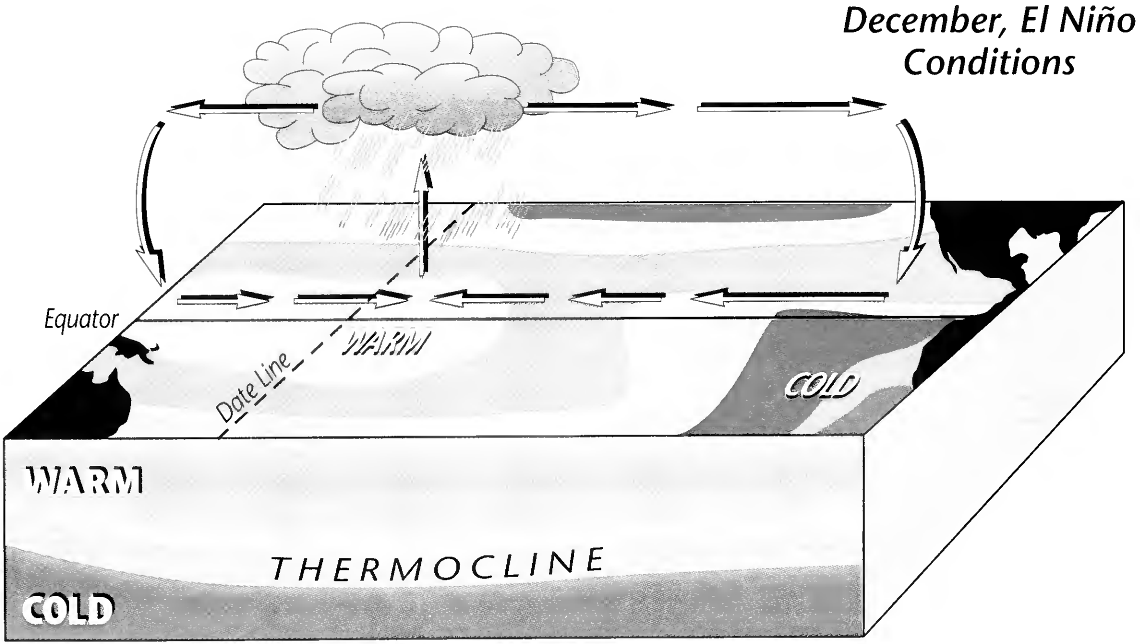
circular argument implies that interactions between the ocean and atmosphere are at the heart of the matter, and that a change in one medium affects the other. Suppose, for example, that during a period of intense trades, a small disturbance causes those winds to relax somewhat. Some of the warm surface waters that are piled up in the west will tend to surge eastward. The associated change in the sea-surface temperature pattern will cause a further relaxation of the winds so that even more warm water moves eastward.

Such positive feedbacks between the ocean and the atmosphere can lead to El Niño. During the process, the atmosphere responds rapidly, within a matter of days or weeks, to changes in sea-surface temperatures. The ocean, however, takes far longer (many months) to adjust to a change in the winds. It is this "memory" of the ocean that makes the Southern Oscillation continual. The oceanic conditions at a certain time are not simply determined by the winds at that time, but also depend on winds at earlier times. During El Niño, for example, the ocean has a "memory" of winds that prevailed during La Niña, and it is the delayed responses to those winds that brings about the termination of El Niño and introduces the next La Niña.

Successful prediction of the 1991 El Niño is convincing evidence of rapid progress during the 1980s in our ability to monitor and predict conditions in the tropical Pacific. The National Meteorological Center now issues not only daily weather forecasts, but also monthly reports that describe surface and subsurface oceanic conditions in the tropical Pacific. This new era of operational oceanography promises to put oceanography on a par with meteorology.

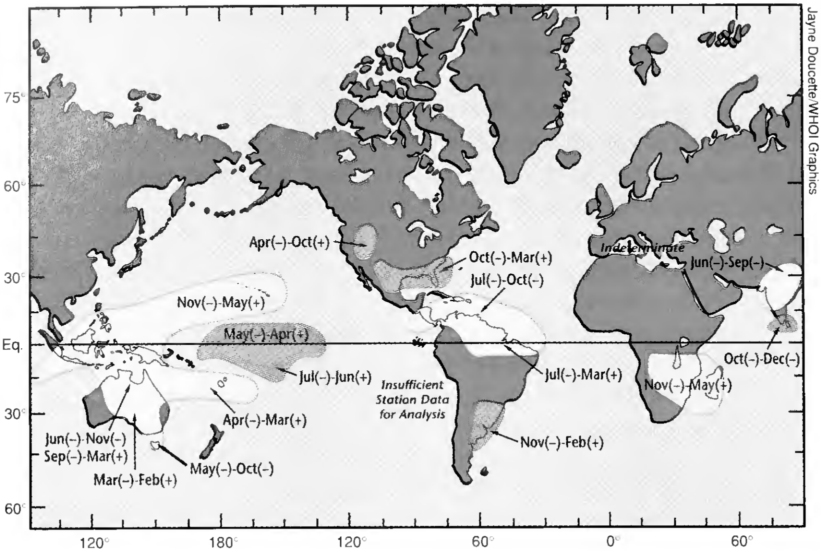
For a long time there has been a sharp contrast between the paucity of oceanographic data and the vast amount of meteorological data flowing continually from a global network of instruments, including satellites. The principal justification for atmospheric data collection is the

In an El Niño year, the trade winds relax, allowing a surge of warm water eastward across the Pacific and changing the characteristics of waters in the eastern part of the ocean basin. (After Verne Kausky, National Meteorological Center.)



December, El Niño Conditions

Jayne Doucette/WHOI Graphics



During an El Niño, precipitation is enhanced in some (pink) areas and diminished in other (yellow) regions. The months indicate when these regions are affected, typically coinciding with local rainy seasons. The year that unusually high sea-surface temperatures first appear is indicated by (-); (+) refers to the following year. (After Ropelewski and Halpert, 1987.)

Jayne Doucette/WHOI Graphics

need to predict the weather. Although the prediction of certain changes in the oceanic circulation (for example, Gulf Stream meanders) serves navigational needs, the most compelling reason for operational oceanography is the need to predict climate fluctuations—El Niño, the difference between one winter or summer and the next, prolonged droughts, and so forth. Such forecasts require coupled atmosphere-ocean models. They start from an accurate description of atmospheric and oceanic conditions at a certain time, and predict how conditions will develop thereafter. Atmospheric descriptions are based on measurements that are interpolated by a realistic computer model to produce global maps of different fields—temperature and winds, for example.

During the past decade, oceanographers have implemented a similar operational system for the tropical Pacific Ocean. The network of instruments that provide data in real time to the Global Telecommunication System includes expendable bathythermographs released by voluntary observing ships, tide gauges on numerous islands, and, in the central tropical Pacific where there are neither islands nor commercial ship tracks, an array of moorings with thermistor chains (TOGA-TAO moorings) and, in some cases, current meters (see Climate Prediction and the Ocean, page 66). A numerical model of the tropical Pacific, capable of realistic simulations of oceanic conditions, assimilates the various measurements and each month produces maps that describe oceanic conditions (surface and subsurface temperatures and currents). These maps are the oceanic counterparts of daily weather maps and depict the evolution, month by month, of El Niño and complementary La Niña conditions in the tropical Pacific Ocean. Because of the success of this effort, operational activities are now being expanded to the global oceans. This development promises considerable benefits for oceanography—however, not everybody welcomes it enthusiastically.

Many oceanographers believe that it is premature to attempt operational oceanography. They agree that it may be possible in the tropics but argue that, for other regions, oceanic computer simulations are still too crude and the oceanographic data collected on a regular basis are too sparse. The skeptics do not appreciate the extent to which the obligation to predict El Niño contributed to rapid progress in tropical oceanography, especially the availability of more data. Samuel Johnson observed that capital punishment concentrates the mind wonderfully. The same can be said of the obligation to make predictions on a regular basis. In the case of El Niño it has led not only to improved models of the tropical Pacific, but also to much more accurate information about the winds that drive the oceans. (The winds, from realistic atmospheric models, received little attention until oceanographers started to use the models and pointed out their deficiencies.)

There is no doubt that attempts at realistic simulations of other parts of the oceans, month after month, will also lead to improved models. As I mentioned, these simulations start from an accurate description of oceanic conditions, a description that requires measurements. In the case of the tropical Pacific, it was clear that there was a need for a TOGA-TAO array to measure subsurface temperatures in the remote central equatorial Pacific. Such an array has been installed, and now transmits its data to certain centers by satellite, twice a day. Operational oceanographic activities for other parts of the oceans are also likely to provide convincing justification for improved global ocean monitoring.

In the current debate about the feasibility of operational oceanography, nonscientific factors seem to play a significant role. Many oceanographers share the sentiments expressed by John Masefield:

> *I must go down to the seas again, to the lonely sea and the sky,*
> *And all I ask is a tall ship and a star to steer her by....*

They are appalled by the prospect of an impersonal, mammoth computer model of the ocean that demands data every 12 hours from all ships, short and tall, at sea. There would indeed be an unfortunate diminution in the romance of the oceans if operational oceanography were to replace the traditional methods of measurements. That, however, will not happen. Both approaches are essential. The ocean is so immensely complex that even the most sophisticated model, many years hence, will still have serious deficiencies. Research expeditions on ships with evocative names—*Atlantis, Discovery, Meteor*—to study poorly understood phenomena and processes will always be necessary to learn more about the oceans and improve the models.

The skeptics do not appreciate the extent to which the obligation to predict El Niño contributed to rapid progress in tropical oceanography.

S. George Philander is Director of the Atmospheric and Oceanic Sciences Program at Princeton University. His 1990 book El Niño, La Niña and the Southern Oscillation *is published by Academic Press.*

TOGA-COARE

Tropical Ocean–Global Atmosphere Program and Coupled Ocean-Atmosphere Response Experiment

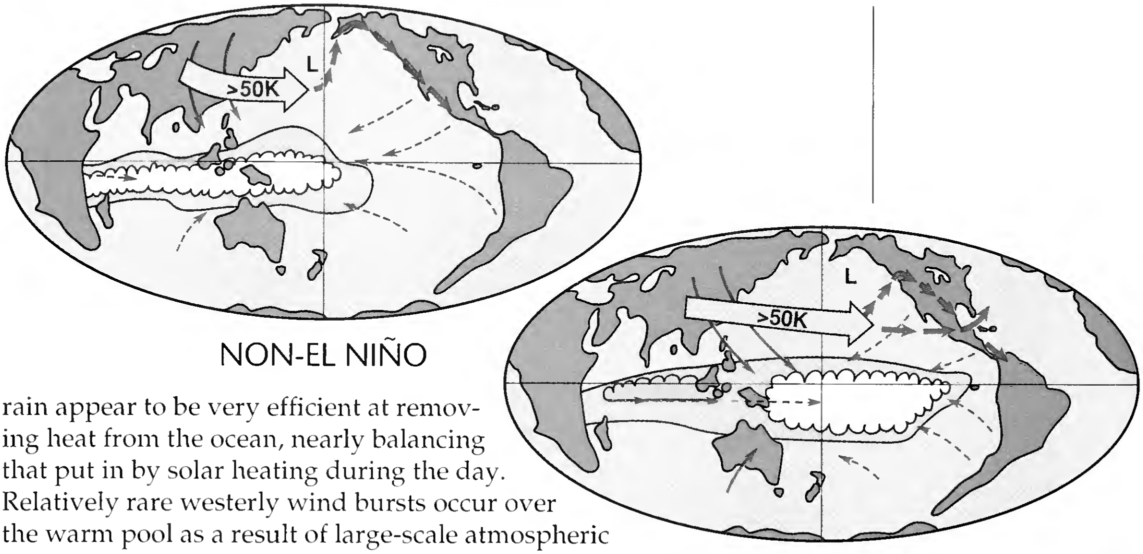
Roger Lukas and Peter J. Webster

With temperatures greater than 29°C, the warm pool contains the warmest open-ocean waters in the world.

Since 1985, scientists working for the Tropical Ocean–Global Atmosphere (TOGA) program have sought to predict seasonal-to-interannual climate variability. El Niño/Southern Oscillation events in 1987 and 1992 were successfully predicted with a coupled tropical Pacific ocean-atmosphere model nearly one year in advance, supporting the hypothesis that variable events like these are predictable. Translating this success into accurate projections of global patterns of rainfall and air temperature anomalies remains a challenge, however, partially because coupled ocean-atmosphere models are still relatively crude. In particular, the warm pool system of the western equatorial Pacific strongly influences the global atmosphere, but simulating this is problematic because oceanic and atmospheric processes that operate at small time-and-space scales are unusually important to the system's maintenance and evolution. These processes are not resolved in present models; instead they are parameterized so that their net impact may be estimated.

With temperatures greater than 29°C, the warm pool contains the warmest open-ocean waters in the world. It covers an area comparable to that of Australia, to a depth of 50 to 100 meters. These high sea temperatures are even more remarkable in view of the fact that this is one of the cloudiest regions in the world, so direct solar heating is much lower than in neighboring regions. Moist air from the Pacific trade winds converges over the warm pool, causing more than 4 meters of rainfall per year, which exceeds local evaporation by more than 1 meter per year (on the average) and results in a relatively thin, fresh layer on top of the warm pool. This stratification strongly influences the dynamics and thermodynamics of the upper ocean and thus other aspects of air-sea interaction.

On the scale of the warm pool itself, the winds are usually light, with frequent calms. However, on the scale of individual clouds and cloud clusters, atmospheric motions associated with vigorous convection and



NON-EL NIÑO

EL NIÑO

The warm pool of the western equatorial Pacific is associated with deep convection and heavy rainfall. In turn, the moist Pacific surface trade winds and Australasian monsoons (thin arrows) converge in this region, feeding the convection. The outflow from the convection occurs at great heights in the atmosphere, interacting with middle-atmosphere westerly jet streams (thick arrows) in the mid latitudes. The eastward displacement of the warm pool associated with stronger-than-usual monsoons and weaker trade winds during El Niño/Southern Oscillation events carries the atmospheric convection into the central Pacific. Jet stream paths are considerably affected, with important consequences for global weather patterns.

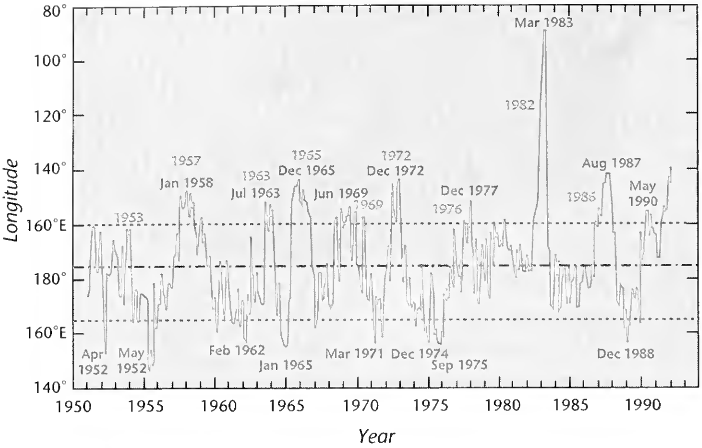
rain appear to be very efficient at removing heat from the ocean, nearly balancing that put in by solar heating during the day. Relatively rare westerly wind bursts occur over the warm pool as a result of large-scale atmospheric events. These wind events may extract huge amounts of heat from the ocean by evaporation, and may also cool the sea surface by mixing the warm pool with cooler waters below. Depending on the strength, duration, and frequency of such wind events, the warm-pool waters may be pushed eastward a significant distance.

Displacements of this coupled system eastward to the central Pacific are associated with the Southern Oscillation and El Niño, and are illustrated by plotting the longitude of selected sea-surface temperatures against time. Strong atmospheric heating over the warm pool from latent-heat release during heavy rains is a major driving force for Earth's atmospheric circulation, and displacements of the warm-pool system back and forth along the equator appear to be responsible for many anomalous weather patterns that influence North America. By comparison, the unusually warm sea temperatures off Peru during El Niño have only localized effects.

The TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) aims to make oceanic and atmospheric observations to develop and test improved coupled models that parameterize small-scale processes more accurately, and that also capture the strong, complex feedbacks between different processes operating in the warm-pool system. Hypotheses about the role of the warm-pool system in climate variability can only be tested by advanced coupled models. Additionally, COARE will provide data sets for developing and validating algorithms for monitoring the warm-pool system from space. An international effort, COARE will take place in a near-equatorial region northeast of Australia from November 1992 through February 1993, with contributions from Australia, China, France, Germany, Japan, Indonesia, Papua New Guinea, Russia, Solomon Islands, Taiwan, UK, and US.

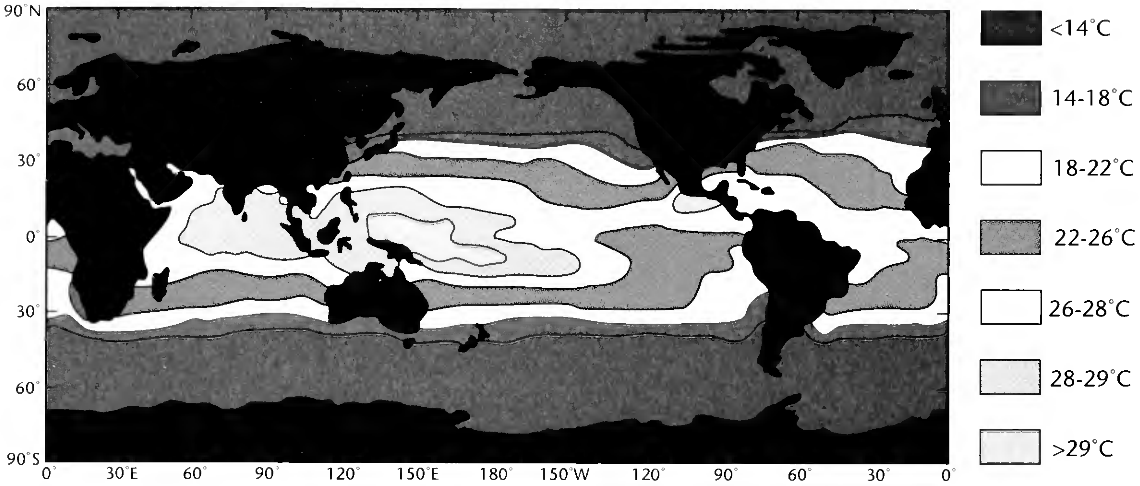
COARE's strategy is to embed high-resolution observations within the coarse resolution, Pacific-wide, long-term monitoring conducted by the TOGA program. The four-month period of intensive observations is confined to the core of the warm pool. The oceanographic component of COARE can be viewed as a three-dimensional mixed-layer experiment, with high-quality observations of local atmospheric forcing and remote ocean forcing. The objective is to determine and quantify the processes that influence the mixing of heat, salt, and momentum. A network of current-, temperature-, and salinity-sensing moorings will provide time series, while shipboard surveys of these properties will be carried out using towed sensors in combination with hull-mounted acoustic current-profiling systems. Upper-ocean turbulence profiles will be calculated from shipboard microstructure observations.

At the air-sea interface, the objective is to determine fluxes of heat, moisture, and momentum that force the ocean. These fluxes are very difficult to estimate, which has presented a serious challenge to both TOGA and the World Ocean Circulation Experiment (WOCE). COARE's strategy is to make direct time-series measurements of these fluxes at just a few shipboard locations, with the aim of developing improvements to their parameterizations, in terms of variables such as air and sea temperature and wind. Aircraft-based flux measurements will be made at selected times over the center of the moored ocean array (covering the area of a square that is 150 kilometers on each side) to place the time series in context and to obtain spatial statistics that relate the turbulent fluxes to changes in convective activity. Measurements of meteorological variables and the improved parameterizations will be made on research vessels and surface buoys, and the improved parameterizations of turbulent fluxes will be used with these observations to provide longer times series and better spatial coverage for comparison with fluxes calculated from atmospheric models and remotely sensed properties. Heat and moisture budgets will also be computed from upper-ocean observations and atmospheric sounding network observations to provide consistency checks on the air-sea flux estimates.



The time series of the monthly average position of the 28.5°C sea surface isotherm along the equator is a good index of the eastward extent of the western Pacific warm pool. Extreme values are associated with ENSO events (eastward displacement) and with cold events (or so-called La Niña events; extreme westward displacement). Considerable variability occurs between these extreme events, and this likely influences mid latitude weather patterns. The improved modeling of these coupled ocean-atmosphere variations is the ultimate objective of TOGA-COARE.

COARE is collaborating with other programs that have an interest in the specific components of air-sea flux. For example, estimating rainfall over the ocean is an extreme challenge being taken on by NASA's Tropical Rainfall Measuring Mission (TRMM). Two shipboard Doppler weather radars will make observations that will be combined with those from aircraft radars and rain gauges on ships and buoys to yield estimates of rain reaching the sea surface in the center of the COARE domain. Estimating the radiative fluxes that influence the vertical distribution of heat in the ocean and atmosphere is another difficult task and both NASA and the US Department of Energy's Atmospheric Radiation Measurement program are working with COARE to obtain atmospheric observations for estimating how much solar heat contributes to the heat budget, and its control by variations in cloudiness. Profiles of penetrating radiation in the upper ocean will be made, and special temperature and surface radiation measurements will help us understand the relationship between the subsurface temperature in the mixed layer and the "skin" temperature that is seen by satellite.



The annual mean sea-surface temperature for the world ocean is shown; colors have been chosen to highlight the distribution in the tropics. The western Pacific warm pool, which is the focus of TOGA-COARE, is shown in red, indicating sea surface temperatures greater than 29°C. (After Levitus, 1982.)

Although many objectives motivate COARE's atmospheric component, the main one is to relate the spatial and temporal modulations of the air-sea fluxes to variations in atmospheric convection, and to relate convective variations to processes on larger scales. The COARE data set will impact climate research for many years, but we have good reason to believe that there will be important early returns. Indeed, on the basis of pilot measurements for COARE, the European Centre for Medium Range Weather Forecasts has changed an operational model to better represent evaporation in the western Pacific warm pool; this in turn resulted in improved model performance for distant regions of the world. Improvements to our coupled ocean-atmosphere models will increase our confidence in numerical experiments for testing hypotheses about seasonal to interannual climate variability; a by-product will be increased confidence in coupled-model simulations of climate variability over longer terms.

Roger Lukas is a surfer from Cape Cod who found warm waters (and better waves) in Hawaii. As a Professor in the University of Hawaii Department of Oceanography, he specializes in equatorial Pacific ocean circulation and thermodynamics, seeking even warmer waters and bigger (Kelvin) waves. In order to schedule his waking life around the surf, he taught himself how to forecast the waves several days in advance. Finding this lead time insufficient, he has been studying interannual climate dynamics so that he can schedule his legitimate research activities a year or more ahead without missing good swells. These studies inadvertently led to the experiment described in this article, leaving him almost no time for surfing.

Peter J. Webster is the Director of a new program at the University of Colorado: The Program in Atmospheric and Oceanic Sciences (PAOS). The Program can be best described as being something between PATHOS and CHAOS. Originally from Australia, he concentrates on equatorial wave dynamics and the interaction of low-frequency phenomena, such as the monsoon and ENSO, in the context of the coupled ocean-atmosphere system. Rumour has it that he really moved to Boulder because he heard that a golf ball goes 20 percent further at high altitude.

Climate Prediction and the Ocean

Modeling Future Conditions

Edward S. Sarachik

It is no exaggeration to say that the ocean is inadequately observed.

Twice a day, all over the world, balloons are released from Earth's surface to measure characteristics of the overlying atmosphere. These measurements are combined with regular satellite observations of the velocity of low clouds, electromagnetic radiation emitted by the atmosphere and clouds, and airplane and surface reports. The atmosphere is therefore regularly and abundantly measured (although never abundantly enough, especially over the ocean). The data is subsequently communicated and exchanged on the Global Telecommunication System (GTS) and is used by weather services in many countries to make weather forecasts. The data is analyzed and archived, and subsequently distributed for research purposes.

By contrast, regular measurements of the ocean's interior are made only from voluntary observing ships, and only as deep as allowed by the wire on an Expendable Bathythermograph (XBT), somewhere around 400 meters. Spatially, these measurements are sparse (they are taken primarily along shipping lanes). Because of shipping schedules, they are also infrequent in time. Sea-surface measurements are far more numerous, as they are routinely taken by drifting buoys and most ships at sea; still, surface measurements are simply not adequate to describe all that is needed. For example, we require measurements below the ocean's surface (where vessels seldom go), at depths greater than those XBTs can reach, and with greater time resolution than a week or so.

Obtaining these requires special efforts by the research community, first in proposing a measurement, then staffing and equipping a cruise and accomplishing the proposed measurements, then finally in using the resulting data for research. The process is expensive and time consuming—even then, the total amount of data collected in the ocean's interior is orders of magnitude less than the amount collected in the atmosphere. It is no exaggeration to say that the ocean is inadequately observed.

Why this difference between the state of atmospheric and oceanic observations? Granted, the ocean is less transparent to light and other standard electromagnetic probes normally used to make and report measurements, but that is not enough to explain the operational nature of atmospheric measurements compared to the primarily research nature of most subsurface ocean measurements.

The essential difference is, I believe, the use of atmospheric data for weather prediction. Until now, no social or economic imperative has required ocean prediction, and therefore no social or economic imperative has driven the establishment of an operational ocean observing system. The factor that may change all of this is the advent of climate prediction, that is, the prediction of average weather conditions at a given place.

Weather Prediction and Climate Prediction

Weather prediction proceeds by:
1) gathering data from various platforms in near real time (usually 6 hours) from the GTS, that is, 6 hours from data collection to its delivery to a forecasting center;
2) controlling the data quality by various consistency checks;
3) preparing a best estimate of the state of the atmosphere from the observations and any other available information;
4) initializing the forecast (combining the estimate from step 3 with any necessary technical adjustments to make the observations consistent with the numerical model);
5) applying equations of atmospheric motion to numerically predict the atmosphere's future state; and
6) comparing the forecasted state of the atmosphere with the measured state to compile validation statistics.

These steps have been carried out twice a day since the early 1960s, comprising a total of over 22,000 analyses and forecasts.

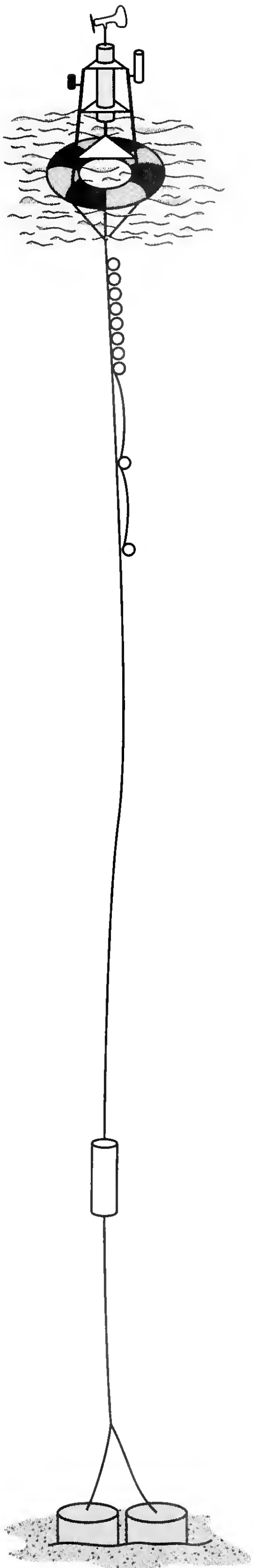
We now know that the atmosphere is a chaotic system: Even if the motion equations are accurately described and the physical models were otherwise perfect, inescapable errors in the estimate of the initial state would grow, eventually large enough to contaminate the forecast. This growth of errors limits our ability to predict the atmosphere to something on the order of two to three weeks. It is, in principle, impossible to predict the detailed state of the atmosphere beyond this fundamental barrier.

So how, then, can we ever hope to predict the climate? How can we scale the predictability barrier to make useful forecasts months—and even years—in advance? The answer is that we cannot escape the limits imposed by fundamental limits of predictability, but we can avoid them by making different kinds of predictions. Instead of predicting the detailed state of the atmosphere, we predict the statistics of the atmosphere. There is no fundamental limit on predicting the statistics of atmospheric flow. Thus if we predict the average seasonal temperature of a region one year in advance, it violates no predictability limit, while if we predict the precise temperature at a given location a year in advance, it does.

How does the ocean enter these considerations? It is commonly accepted that the atmospheric climate, meaning the statistics of atmospheric weather, can be simulated with general circulation models by specifying the lower boundary condition that the ocean provides, namely, the sea-surface temperature (SST). In particular, seasonal

John C. Stennis Space Center

Since 1981, more than 56 C-MAN (Coastal-Marine Automated Network) instrument platforms have been engaged along US coasts and the Great Lakes to obtain atmospheric and oceanographic data. C-Man stations may be lighthouses, like this one at Stannard Rock, Michigan, offshore or onshore platforms, or moored buoys. Sensors for humidity, rain, solar radiation, water temperature, water level, wave height, subsurface salinity, and light intensity now relay data to shore via satellite at hourly intervals. (Courtesy J. Howe.)


Atlas mooring
Jack Cook/WHOI Graphics

variation of the atmospheric statistics, the "climatology," is determined by seasonal variations in the quantities external to the atmosphere, in particular solar radiation and the lower boundary condition, the SST.

We see that if it were possible to predict the SST (and other slowly varying boundary conditions) a year or so in advance, then the statistics of the atmosphere could also be partially determined a year or so in advance. If it were possible to predict all the slowly varying boundary conditions (land surface conditions and SST), then the best possible prediction of climate could be made. The ocean enters the climate prediction problem through the determination of SST, the only oceanic quantity that the atmosphere sees. The tool for predicting SST is a coupled atmosphere-ocean model.

Coupled Atmosphere-Ocean Models

What determines SST evolution? As it turns out, SST variability is determined by processes on both sides of the air-sea interface.

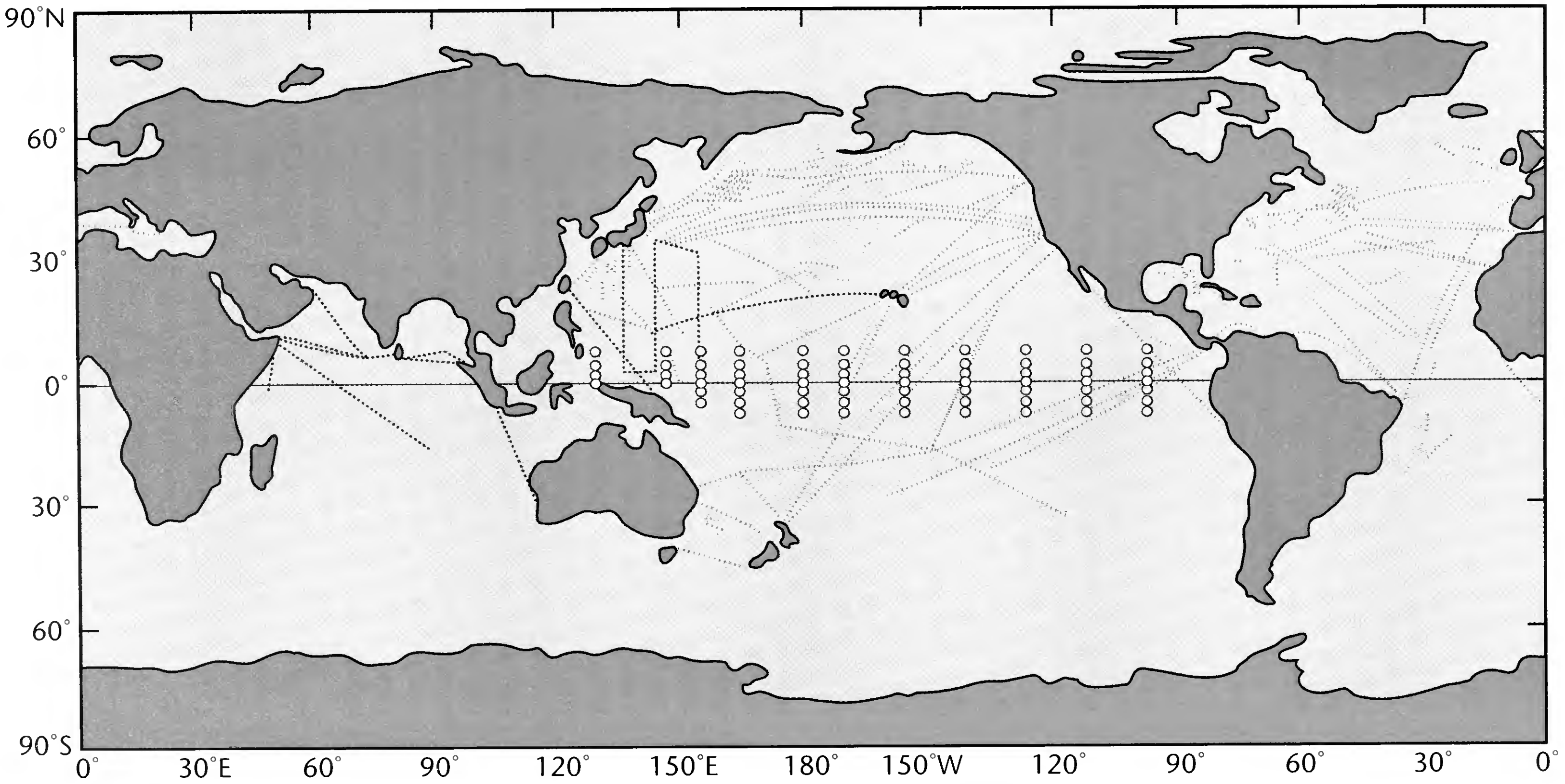
Any atmospheric variation that affects the heat flux at the ocean's surface will also affect the SST, including:

- a change of cloudiness, which affects both solar and infrared radiation at the ocean's surface,
- wind speed changes, which can alter evaporation at the ocean's surface, and
- a change in the gaseous or aerosol composition of the atmosphere, which affects radiation at the ocean's surface.

Similarly, there are a number of ocean processes that affect the SST. The SST may be considered the temperature of the ubiquitous mixed layer (by definition, a layer of almost constant temperature that underlies most of the ocean surface; see Dynamics of the Ocean Mixed Layer, page 46), so that any ocean process that affects the mixed layer may also affect the SST. For example, a change in the intensity of upwelling beneath the mixed layer will change the influx of colder, deeper water into the mixed layer and will therefore change the SST. A change in horizontal velocities near the surface will change the advection of warm or cold water (depending on the nearby water temperature) and change the SST. A change in the mixed layer depth itself will change the mixing of colder waters into the base of the mixed layer, and will change the SST.

We conclude that, since variations of SST depend on processes on both sides of the air-sea interface, the only way to calculate SST evolution is to couple an atmospheric model to an ocean model and consider the mutual and consistent evolution of the atmosphere and the ocean. While this is easy enough to say, experience has shown that coupling a well-understood atmospheric model to a well-understood ocean model produces a coupled model whose characteristics cannot be determined in advance. The problem seems to be that each model is particularly sensitive to small errors in the other model, errors that go undetected when one model is run with the other model held fixed or otherwise specified.

Despite these start-up difficulties, coupled atmosphere-ocean models are now in a rapid stage of development. They have been especially successful in explaining and predicting aspects of the El Niño-Southern Oscillation (ENSO) phenomenon (see El Niño, page 56). Because computer resources are a limiting factor in running large coupled models, we



Jack Cook/WHOI Graphics

In the Pacific Ocean, water temperature as a function of depth is routinely measured when voluntary observing ships drop XBTs (expendable bathythermographs) while en route, shown above with dotted tracings. Note how these tracings follow the major shipping lanes. The full TOGA-TAO array (shown as red and yellow circles arranged around the equator) augments those measurements, gathering wind, temperature, and current data. Yellow circles indicate Atlas wind and thermistor moorings like the one on the facing page, and red circles indicate current-measuring moorings.

expect that progress in coupled atmosphere-ocean modeling will accelerate as computers become more and more capable.

Short-Term Climate Prediction

We call climate predictions that are one season to a year or two in advance "short-term" climate predictions. Knowing that the tool of climate prediction is a coupled atmosphere-ocean model, how do we go about making short-term climate predictions? Is there any reason to believe they will be successful?

We call climate predictions that are one season to a year or two in advance "short-term" climate predictions.

We already know that skillful predictions of ENSO aspects are possible because they have been demonstrated. A seminal coupled model, built by Mark Cane and Steven Zebiak (Lamont-Doherty Geological Observatory), has proved successful at simulating the atmospheric and oceanic anomalies characteristic of ENSO over the tropical Pacific. This model has been used to predict the onset and failure of ENSO warm phases a year or so in advance.

The Cane-Zebiak model is simplified, in that mean climate and seasonal variations of the atmosphere-ocean system over the tropical Pacific (the "climatology") are specified and only deviations from normal annual variations are simulated and predicted. Predictions are made by initializing the ocean component of the model, and then allowing the coupled model to run freely into the future. The atmosphere slavishly follows SST variations in the tropics, and need not be separately initialized in this model.

Experiments with this model have shown that 1) the "memory" of the coupled system is in the ocean (the ocean's initial thermal state carries most information about the future evolution of the coupled atmosphere-ocean system); and 2) initial errors in the specification of the ocean state grow slowly, on time scales of many months, so that useful predictions a year or more in advance are possible. The first point is essential to the entire prediction enterprise, and shows that measuring the upper ocean's temperature structure is a sufficient initialization for the coupled system to provide useful predictions.

As more complex coupled general circulation models, such as the one pioneered by George Philander (Princeton University), become capable of simulating ENSO with some realism, a more thorough initialization, including more detailed descriptions of the upper ocean and the atmosphere, becomes possible. But how can we measure the temperature structure of the entire upper ocean, say once a month, to make predictions a year or so in advance?

One of the great successes of the US contribution to the international Tropical Ocean/Global Atmosphere (see TOGA-COARE, page 62) program is the creation of the TOGA-TAO (Tropical Atmosphere-Ocean) array for measuring the internal thermal structure of the tropical Pacific Ocean. The fully deployed TOGA-TAO array will consist of 65 surface-moored thermistor chains and surface meteorological measurements, all transmitting the data directly to the GTS. Thus the measurements most useful for initializing the tropical oceans, namely the atmospheric surface winds and upper-ocean temperature, will be available in real time for forecasting. The surface data will be useful in operational weather prediction efforts, and the suite of global atmospheric weather forecasts will be used for initializing the atmospheric component of the coupled model. The TOGA-TAO array will therefore function similarly to the meteorological balloons sent aloft twice a day. It is the first operational oceanographic monitoring array whose data will be available to the entire community in real time, and that can be used for regular and systematic climate prediction.

We envision that the TOGA-TAO array will demonstrate its usefulness by increasing the accuracy of SST prediction and other aspects of ENSO, on seasonal-to-interannual time scales in and around the tropical Pacific. When and if the TOGA-TAO array proves itself, it will be expanded to other tropical oceans and perhaps to mid latitudes, if mid-latitude predictability is shown to exist.

The TOGA-TAO array is the first operational oceanographic monitoring array whose data will be available to the entire community in real time.

Long-Term Climate Prediction

While the possibility of predicting aspects of ENSO a year or more in advance has been proven, the prospects for longer term predictions are not nearly as well defined. We know, for example, that coupled atmosphere-ocean models are used to "predict" the state of the climate in the year 2050, when atmospheric carbon dioxide will presumably have doubled. None of these "predictions" use an initialization of the current state of the ocean, so they seem to be predictions of a different type than we previously discussed.

To understand this difference, we will simply classify predictions into two classes: those that require initialization of the ocean, and those that do not. Presently we do not know at what lead time predictions can no longer make use of ocean initialization. The way to think about this is to consider what aspects of ocean initialization lead to climate predictability.

The ocean is driven from the surface by heat and momentum fluxes. An initial state of the ocean will only lead to long-term predictions if we know how the ocean's thermal state, and in particular the SST, will evolve. In the tropics, specifically the tropical Pacific, two peculiar conditions hold: 1) changes in the upper-ocean thermal field can be easily calculated by simple theory; and 2) atmospheric circulation is very tightly coupled to SST, so that evolution of the SST predictably leads to evolution of atmospheric circulation, which in turn drives the SST.

The combination of these factors makes the tropical atmosphere-ocean system in the equatorial Pacific particularly predictable from the initial state of the upper ocean. The prediction accuracy degrades as we go to longer and longer prediction lead times because errors in the initial specification inevitably grow (due to instabilities and noise) and we must go deeper in the ocean to initialize a longer forecast (as the lead time increases, the ocean volume that communicates with the surface during those times is expected to increase). Motions in the deeper ocean are feebler, temperature structure is less stable, and measurements become more difficult and require greater accuracy.

At higher latitudes, linear wave theory is not nearly as complete a description as in the tropics, and the atmosphere, while affected by the SST, is by no means as reliably dependent upon it. This means that the mid-latitude atmosphere-ocean system is not as predictable as the tropical coupled system, and we expect our forecasting skill to degrade as we move poleward. It is true, however, that some mid-latitude prediction skill exists, because some mid-latitude atmospheric responses depend on tropical SSTs. We also expect that forecasting skill will degrade as the range of the predictions increases at higher latitudes; the lack of a tight coupling of the atmosphere and the SST implies that natural atmospheric variability will eventually degrade the forecast accuracy.

Therefore, predicting skill cannot be expected to be as high in mid latitudes as it is in the tropics. As the lead time for prediction increases, the skill level will depend on the initialization of deeper and deeper parts of the ocean. Ultimately the entire ocean volume must be initialized for a forecast of *n* years, where *n* is still not known. Beyond this time, the SST cannot be predicted with any skill whatsoever, and we make the transition from predictions that can make use of initialization to those that cannot.

Climate prediction will change the way oceanographers work and think.

This does not mean we can know nothing about mid-latitude SST in the second class of predictions. We can know its mean value and its natural variability even though we cannot predict what its likely value will be at any given time as it fluctuates through its variability. It is in this latter sense that predictions of the climate system's response to increases in greenhouse gases must be understood. The best we can do is predict the mean values, the SST variability, and the statistical response of the atmosphere; we cannot predict the actual values at any given point.

A Vision of the Future

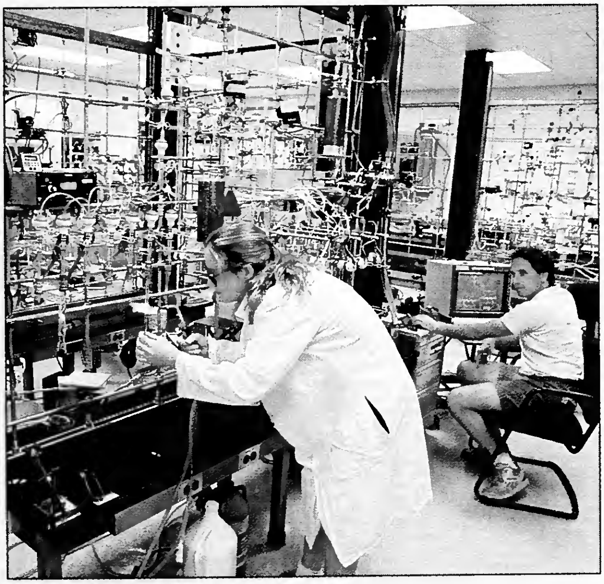
The challenge for climate prediction in the future is to

- build prediction and observation systems that demonstrate the maximum possible skill in tropical predictions of a year or so in advance,
- learn to what extent we may expect to achieve accuracy in initializing the mid-latitude oceans,
- learn what the ultimate limit of predictability is when the entire ocean volume is initialized, and
- build the operational observing systems needed to take advantage of the demonstrated skill.

The observation system used to initialize the ocean is crucial for the future of climate prediction and, indeed, for the future of oceanography as a discipline. Regular and systematic measurements of the ocean, supported by consensus and resources of the global community, taken in an operational mode and distributed instantly, can be expected to have the same impact on the science of oceanography that the observing system for weather prediction had on the science of meteorology. We can expect that this increase in ocean data will lead to a burgeoning of knowledge about the ocean, and a new infusion of interest in a science that will be well on its way toward having a firm observational base.

Climate prediction will change the way oceanographers work and think, similar to the way that satellite observations have forced oceanographers to think differently about the ocean. The days of limited measurements laboriously taken in a research mode is coming to a close, and opportunities for understanding the ocean as part of the climate system will grow enormously as the measuring systems become operational. The future of oceanography as a profession will depend on how it responds to the challenge of climate prediction.

Edward S. Sarachik is Research Professor of Atmospheric Sciences at the University of Washington, and serves as the Chairman of the Science Working Group for T-POP (the TOGA Program on Prediction). His research interests include tropical meteorology and oceanography, the ENSO phenomenon, predictability of the climate system, and the role of the ocean's thermohaline circulation in climate variability.



WOCE

The World Ocean Circulation Experiment

George T. Needler

The World Ocean Circulation Experiment is designed to improve our understanding of the full-depth global ocean.

Earth's climate system is a dynamic regime driven by radiative energy from the sun. More than half this energy is received by the ocean, where it may be directly given up to the atmosphere or stored and sometimes moved great distances by ocean currents. Fresh water is exchanged with the atmosphere at the ocean surface through precipitation and evaporation. Winds force ocean currents, some of which carry warm water poleward where heat is given up to the atmosphere. In the North Atlantic, this causes the climate of western Europe to be more moderate than it would be without an oceanic heat supply. As water releases heat to the atmosphere at high latitudes, it cools and, becoming heavier, sinks into the deep ocean, sometimes to the bottom, where it may remain isolated from the atmosphere for decades to centuries.

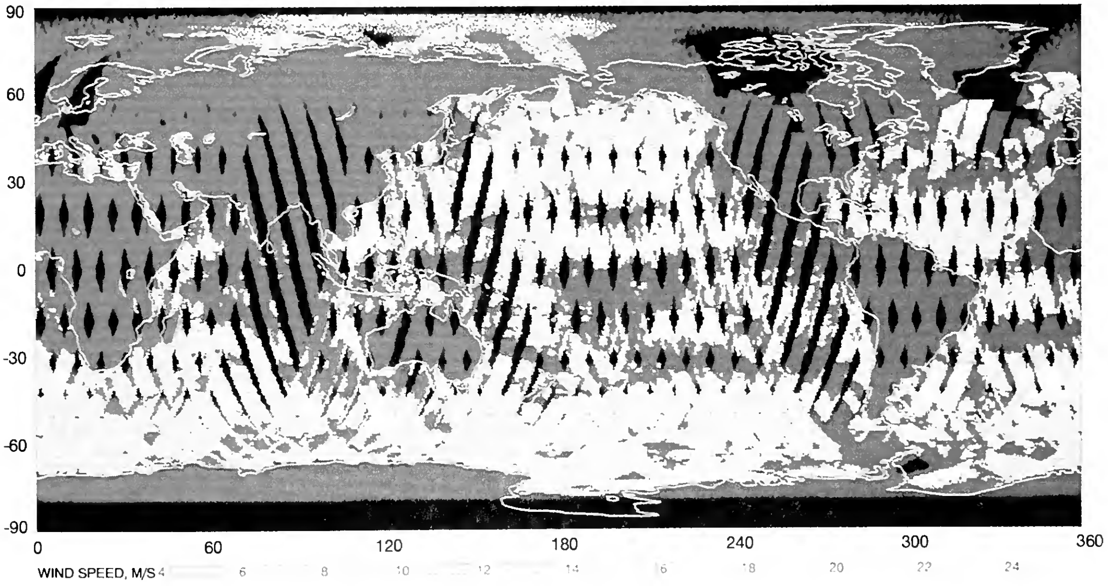
The ocean plays a major role in Earth's climate system, and the prediction of climate change is a critical environmental objective of our time (see Climate Prediction and the Ocean, page 66). Although attention is often focused on the climatic impact of human activities, such as the production of carbon dioxide and other greenhouse gases, natural climate changes are known to occur on time scales from months to years, decades, and longer. Predicting these changes would bring great benefits to society.

The dominant climate change on shorter time scales is El Niño-Southern Oscillation (ENSO), whose best-known signal is the occurrence of unusually warm water in the eastern Pacific (El Niño) with disastrous impacts on local fisheries (see El Niño, page 56). Research into the ENSO problem is carried out by the Tropical Ocean and Global Atmosphere experiment (see TOGA-COARE, page 62), a program complementary to WOCE within international climate research. Some predictions of El Niño are now possible.

Over longer periods, from years to decades, the ocean at greater depths and higher latitudes is involved in the regulation of climate and its changes. The World Ocean Circulation Experiment (WOCE) is designed to improve our understanding of the full-depth global ocean as a step toward more scientifically rigorous climate predictions on these time scales. WOCE is the first research program of sufficient scope to mount a truly global investigation of the ocean. Scientists from oceanographic institutions and government agencies around the world are participating in this cooperative experiment; indeed, only this breadth of participation makes WOCE research possible.

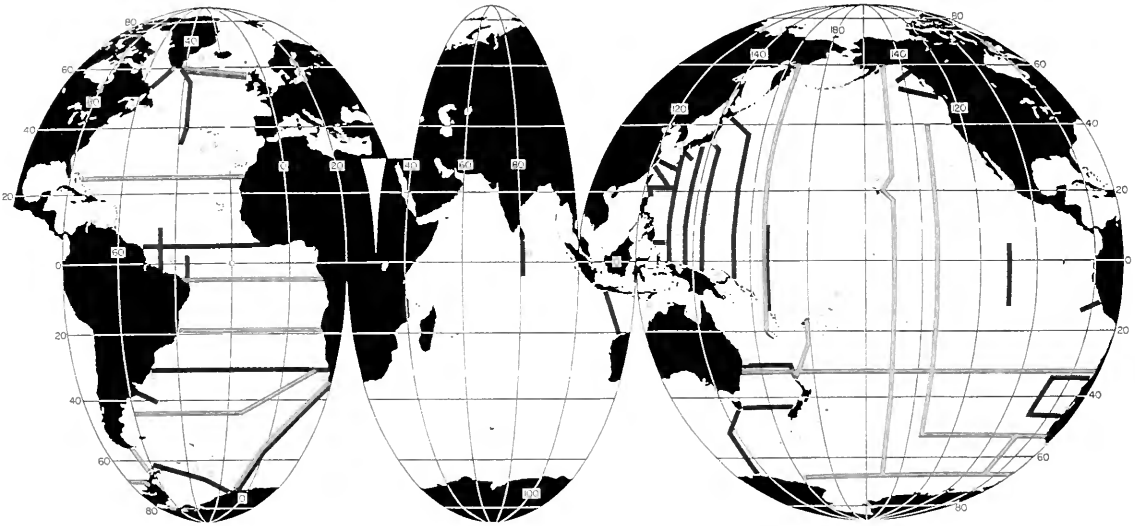
Global ocean coverage provided by satellite-borne sensors is a vital component of WOCE. Of particular importance are the altimeters and scatterometers on the European Space Agency's ERS-1 (launched in July 1991) and ERS-2 (to be launched in 1994) missions, the precision altimeters on the joint US/France TOPEX/POSEIDON mission (to be launched in July 1992) and NASA's scatterometer NSCAT to be flown on Japan's ADEOS mission in 1995. Scatterometer measurements allow scientists to directly estimate surface wind and wind stress over the ocean, especially when the measurements are assimilated into atmospheric circulation models with in situ data. The coverage that ERS-1 provides is shown in the figure below. Wind stress drives large oceanic gyres and western boundary currents such as the Gulf Stream. Altimeters measure changes in sea-surface elevation, and enable oceanographers to calculate ocean currents in much the same way that meteorologists calculate winds from atmospheric surface-pressure maps. A more accurate description of Earth's surface-gravity field or geoid (see Observing Ocean Circulation from Space, page 9) is needed for maximum utilization of altimeter data. To obtain a detailed gravity-field mapping, a special mission is required as the satellite must fly very close to Earth. The European Space Agency's ARISTOTELES is designed for this purpose. Although slated for launch in the mid-1990s, the mission has yet to be funded.

In the ocean interior, beyond the reach of satellite sensors, the WOCE field program is providing a relatively uniform and comprehensive description of global ocean circulation to a level of detail only previously attempted in limited regions. At about 8,500 hydrographic stations along 230,000 nautical miles of section tracks, one-time measurements are being made of the full-depth distribution of temperature, salinity, oxygen, and nutrients. Measurements of transient tracers such as helium-3, tritium, and chlorfluorocarbons, which have been introduced into the ocean only



This map details the wind speed as given by the ERS-1 scatterometer over a three-day period. Dark blue areas are where land has affected the measurement or the wind speed is below 4 meters per second. Scatterometer data was not available at high northern latitudes on some passes when measurements were being made. Where one pass intersects another, the data from the later pass is presented. Since weather patterns will have shifted over the three-day period, care must be taken when interpreting the map. (Courtesy ESA/ESRIN, ESA Product Control Service.)

during the last few decades, enable tracking of water masses that have been in contact with the atmosphere during that time. In cooperation with the Joint Global Ocean Flux Study, elements of the ocean carbon cycle are being measured with the primary aim of estimating the uptake of anthropogenic carbon dioxide. Some of the sections will be occupied a number of times to observe changes throughout the WOCE period; this requires an additional 14,000 stations and 500,000 nautical miles of section track. About 1,100 neutrally buoyant floats are being released at depths of 1,000 to 2,000 meters to map deep circulation, many in regions where the deep flow has never been directly measured. Current-meter arrays are measuring the strength of boundary currents and flows through passages. Tide gauges are measuring the sea-surface elevation in support of altimeter measurements.



These WOCE elements will be in progress or complete by the end of 1992. Red lines show the one-time hydrographic sections; green lines, repeat hydrographic sections; and yellow lines, high-quality sections completed shortly before WOCE began in 1990. The blue dots are current meter arrays; the orange dots are occupied hydrographic time-series stations.

The WOCE field program officially started at the beginning of 1990, and soon afterward the German research ships *Polarstern* and *Meteor* were deploying a current-meter array across the Weddell Sea and occupying hydrographic sections across Drake Passage and on to South Africa. The field program is now scheduled to be complete by 1997, with most effort in the Southern Hemisphere early in WOCE followed by work in the Indian, North Atlantic, and Pacific oceans.

The upper ocean is also receiving special attention during WOCE. Current-following surface drifters are being deployed globally and will provide sea-surface temperature for calibrating measurements from space. Later in WOCE, researchers expect these drifters to provide air-pressure data as well. A fleet of voluntary observing ships expands the network of expendable bathythermograph temperature readings. Most of this data is transmitted on the Global Telecommunications System of the World Weather Watch for input into atmospheric weather prediction models. This allows inclusion of all available oceanic and meteorological data, including satellite measurements, in the computation of air/sea fluxes of momentum, heat, and fresh water. Present atmospheric and oceanic estimates of the meridional heat flux often differ by the magnitude of the flux itself, and may be a substantial source of error in climate-change predictions from coupled atmosphere-ocean models. Thus, meteorologists and oceanographers are cooperating to improve surface-flux calculations and their distribution in space and time by using WOCE measurements over the full ocean depths, which provide the best available estimates of air-sea exchange of heat and fresh water over large areas and periods of a year or two.

Ocean models are an integral part of WOCE, and the basic goal of WOCE is to provide ocean models suitable for prediction of decadal climate change. The data collected through WOCE will be analyzed using models to provide a consistent picture of the global circulation, and, as necessary, the models will be modified in ways that make a consistent picture possible within our knowledge of ocean dynamics. This will be aided by the ever-increasing power of computers, which now allows creation of global models that can resolve ocean eddies, the ocean's equivalent to the atmosphere's high- and low-pressure systems. Later in WOCE, the North Atlantic will be sampled more intensely than is possible for the global ocean. The data sets obtained will describe in some detail the oceanic response to atmospheric forcing, and will enable tests of ocean models not now possible.

The basic goal of WOCE is to provide ocean models suitable for prediction of decadal climate change.

Ocean scientists are now spending considerable effort designing ocean observing systems not only for monitoring climate change and understanding its nature but also for collecting the ocean data necessary to initialize future coupled atmosphere-ocean models that will be used for climate-change prediction. WOCE will play a critical role in both improving ocean models for this purpose and determining the data needed to initialize them.

Resources for ocean climate research have not achieved the hoped-for levels in many nations. This has led WOCE to make some adjustments in the timing of the experiment and, in some cases, its observational strategy. Although this has not yet seriously altered the scientific integrity of the experiment, future loss of resources will increasingly affect WOCE's ability to meet its stated goals. This would impact not only our ability to model physical changes in the global climate but also the ocean's biogeochemical nature. The future success of WOCE clearly depends on the resources and cooperation of many nations.

George T. Needler is a physical oceanographer who has spent most of his career at the Bedford Institute of Oceanography (BIO) in Nova Scotia. In 1985, he left his position as Director of the Atlantic Oceanographic Laboratory at BIO and moved to the UK to become the first Scientific Director of WOCE and to establish its International Planning Office at the Institute of Oceanographic Sciences Deacon Laboratory. He returned to BIO in the summer of 1991 while remaining Chief Scientist of the experiment. After seven years of planning WOCE and seeing its initial implementation, he is now ending his formal association with the experiment. He has rejoined the scientific staff of BIO and is looking forward to spending more time doing, rather than planning, ocean climate research.

Physical Oceanography

Old Friends, New Agendas

Peter B. Rhines

But what, in practice, is physical oceanography today, and what will it become tomorrow?

As the 20th century closes, we look back on a wonderful history of physical oceanography's development. Converging streams of polar exploration, theoretical physics, Darwinian evolutionary discoveries, the writing of Earth's climate history, and the idea of massive government funding for basic research all have flowed together to form what we now see as our field. It is a remarkable tale of observational discovery and deductive modeling. But what, in practice, is physical oceanography today, and what will it become tomorrow?

At his general examination, a Massachusetts Institute of Technology-Woods Hole Oceanographic Institution (MIT-WHOI) joint program student once answered the question this way: "It is finding out where the water comes from, where it is going, and what happens to it on the way." But are we just the plumbers of the sea, checking invisible pipes with expensive flow meters, while other, more creative people study its chemistry and biology, and try to predict the climate change the sea may stimulate? I don't think so, and will bring up some of these multidisciplinary matters later in this article. But first let us look at physical oceanography by itself.

Exploration is an important part of our scientific ancestry. Polar adventures, whaling, fisheries, and growing commerce carried ships in great numbers around the Atlantic and across the Pacific to China beginning in the late 18th century. Astute observers like Benjamin Franklin, purely a traveler, and Fridtjof Nansen, an adventurous explorer in search of the North Pole from 1893 to 1896, made real scientific discoveries during their long voyages. Along with the more routine elements of the world's navies, they began to chart the mean circulation of surface waters and the ocean's depth. There were probably many more sailors and sea captains intimate with the workings of the upper ocean and the weather at sea in the 19th century than there are now.

The relative smallness of the community of oceanographers has allowed each of them to keep in mind a relatively broad picture of the science. A young oceanographer can still hope to develop a model or theory of a part of the circulation, and also go to sea to examine it in "total immersion"; that is, nearly around the clock for several weeks. He or she will never forget what that piece of ocean looks like. Keeping in touch with reality and with ideas is the essence of oceanography, and working with a ship's crew and government officials in out-of-the-way countries, as well as university colleagues, breeds a certain friendly tolerance.

Even in those early days, there was a creative tension between outdoor exploration and indoor deduction. It is the development of classical physics that has given us an intellectual basis for understanding the sea, and may have helped us become better shipmates: Agreeing on basic principles does wonders for a relationship. Yet ocean/atmosphere natural science has had and still has an up-and-down relationship with physics, as one can see by reading about the history of the Nobel Prize and discovering why mathematics, oceanography, meteorology, and sundry other areas were left outside the Nobel corral (for an interesting description, read R.M. Friedman's article, Nobel Physics Prize in Perspective, in *Nature*, volume 292, 1981).

Fortunately, a series of discoveries in "natural fluid dynamics" has repeatedly come to the attention of physicists and mathematicians, and works to bring the fields back together. "Chaos" is the new science of complexity in physical systems that nevertheless evolve according to simple, explicit rules (a good book on this subject is James Gleick's *Chaos*). It was largely invented by MIT meteorologist Edward Lorenz as a simple model of atmospheric circulation. It is sometimes described with the mixed compliment as "the greatest 20th-century discovery in classical physics." Boundary layers, which led to the mathematics of matched asymptotic expansions and singular perturbation theory, first arose in the physics of fluid flow around airplane wings and in the ocean/atmosphere.

Agreeing on basic principles does wonders for a relationship.

The Physical Ocean

We describe the fluid ocean principally by eastward, northward, and vertical velocity, and by the prime contributors to its density: temperature, the concentration of dissolved salts, and pressure. Numerous other variables like sea-surface elevation are also involved, but mapping—and then understanding—water movement and density is a primary activity of the physical oceanographer. Deep oceanic waters are about 0.2 percent more dense than surface waters, and though this does not sound like a lot, the enormous size of the deep ocean makes it a very stable fluid that is not inclined to "roll over." We can thus map not only the depth of the sea, but also the depths of an infinity of "neutral surfaces," paths where fluid can move freely (in exchange for other fluid moving to replace it) without doing work against gravity. The neutral surfaces that are deepest and "heaviest" rise to touch the sea surface in the high-latitude oceans in the thermohaline circulation described earlier in this volume; in these small, special regions the atmosphere has an open window on the deep ocean. From charts of water movement along (and more gradually across) the neutral surfaces, there begins to emerge a great, interlocked global flow that owes its origins both to the cold winds blowing at the poles and the harshly contrasting heating, cooling, evaporation, and precipitation at the tropical sea surface. This flow and the atmosphere itself are equally important in carrying heat and moisture between equator and poles, and hence in moderating Earth's climate.

If the oceans were made from rubber, they would respond to atmospheric and tidal forcing with great gelatinous oscillations throughout their full depth.

A mark of real advance in a science is the discovery of simple underlying rules or properties. In geology, Alfred Wegener propounded that solid Earth in many ways acts as a fluid; the field of plate tectonics that grew from this idea gave us a totally new vision of drifting plates and floating continents on the supposed "solid" Earth. In physical oceanography, ironically, we tell our students that the fluid ocean has some of the properties of a solid: The ocean viewed at the global scale is endowed with a stiffness by Earth's rapid rotation. A relationship known as the Sverdrup equation, which describes this "stiffness" of oceanic fluid measured along lines parallel with Earth's rotational axis, is perhaps our paradigm for large-scale ocean circulation. Physical oceanographers have long been men and women of few words, however, so the rest of the world does not hear as much about Sverdrup as about tectonics. Harald U. Sverdrup's equation may be written

$$v = (R \tan \Phi)\, dw/dz$$

where v is north-south velocity, dw/dz is the rate of change of vertical velocity, w, with depth, z, and the quantity $(R \tan \Phi)$ is the radius of Earth times the tangent of the latitude. This is really a simple geometrical statement in disguise. Owing to the "stiffness" property described above, ocean currents, though different at different depths, tend to maintain the spacing between different neutral surfaces, when that spacing is measured not vertically but along the polar axis. It connects the north-south and up-down velocity of the ocean, and hence becomes the cornerstone of any theory involving the great circulation that carries heat, mass, and trace chemicals between equator and poles.

Essential Waves

Another idea of overriding impact is that of the Rossby wave. If the oceans were made from rubber, they would respond to atmospheric and tidal forcing with great gelatinous oscillations throughout their full depth. The same quantity that describes fluid "stiffness" in Sverdrup's equation also hints at a sort of elastic oscillation in ocean waters. This was discovered by the dynamicists Hough, Goldsbrough, and the Swedish atmosphere/ocean dynamicist Carl-Gustav Rossby earlier in this century. A Rossby wave is not a surface wave of the familiar sort, but a great undulation of the whole ocean mass that carries "signals" from one shore to another over weeks, months, and years. This idea of wave propagators is central to oceanic theory.

Several sorts of waves internal to the ocean rely on Earth's rotation and/or spherical shape, variations in ocean depth, or the gradation of water density with depth. The various wave types help to explain many facets of oceanic movement, including:

- why the tides are amplified at the seacoast, compared with mid-ocean regions (and amplified on the French coast relative to the English Coast just across the English Channel);
- why the western sides of oceans are rich with unsteady currents propagated in wind-driven regions far to the east;
- how intense flows through straits like Gibraltar are determined;
- why the top of the ocean oscillates with the period of a Foucault pendulum; and

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- how energy and momentum originating in the atmosphere penetrate deep into the sea.

What is more, such waves are equally potent in the atmosphere. Rossby waves are an essential part of the high- and low-pressure centers that progress across the daily weather charts. And, when an El Niño event warms the equatorial waters of the central Pacific, it stimulates a far-reaching train of Rossby waves in the atmosphere (mixed with instabilities of the westerly winds) that affects weather over North America and beyond for many months (see El Niño, page 56).

Waves also lead to other important events: mixing and mean circulation. The work done (say, by the atmospheric winds) to generate waves creates both energy and mean flow in the sea that remain even after the wave dies away. On the one hand, this may be the main mechanism by which water masses in the deep ocean subtly and slowly blend together, mixing across neutral surfaces; on the other hand, it gives us a way to understand the generation of large-scale ocean currents. In particular, we now have simple theoretical models that show how Rossby waves generate intense western boundary currents in each major ocean (see Box, page 26), determine the depth to which wind-driven currents penetrate downward from the sea surface, and how global circulation in the abyss develops in response to an intense input of cold, heavy water from the high-latitude ocean surface. In this latter case, topographic waves find their way from high latitudes toward the equator at the western sides of the ocean, then travel along the equator, then poleward along the eastern margins, and finally radiate westward as Rossby waves within the body of the ocean. As a final example, theories that are beginning to successfully predict El Niño events involve wavelike "triggers": eastward Kelvin and westward Rossby waves bouncing between continental boundaries along the Equatorial Pacific.

Rossby waves are an essential part of the high- and low-pressure centers that progress across the daily weather charts.

Theories, Models, Observations

If the interaction of such ideas with observations characterizes modern ocean research, which comes first, theory or observation? This is often debated—without much light being shed. No doubt the framing of the important problems in oceanography stemmed from early observations. At each stage, however, theoretical models have provided both essential tools for analysis and mathematical solutions for complete, though idealized, flow problems. The thermal-wind equation, for example, is a simple relation connecting horizontal variations of fluid density (for example, fronts) and vertical variations in flow speed. It is the basis for relating observations of fluid density (through temperature, salinity, and pressure) to horizontal velocity in both atmosphere and ocean. The thermal-wind equation was discovered in 1898 by Wilhelm Bjerknes, who was a part of the remarkable Norwegian "Bergen School" of meteorologists. They were trying, in Bjerknes's words, to "transform the inexact science of meteorology into an exact physics of the atmosphere."

In my own experience, I can see the nonsense of asking too earnestly whether observation leads or follows theory. When Bill Young (Scripps Institution of Oceanography) and I were developing circulation models in the late 1970s, we predicted something about the structure of the wind-driven circulation, which occupies the top kilometer or so of the ocean, and the eddy, wave, and mean-flow processes that are influential in shaping it. It was more important, however, that we focused on the central role of a quantity called the potential vorticity. At the large scale of the circulation, potential vorticity is simply related to Sverdrup's equation. It is proportional to the length of a line of fluid drawn parallel to Earth's axis, and terminating on two adjacent neutral surfaces. Potential vorticity conservation is once again expressing the fluid "stiffness" on a rotating Earth. I had never seen maps of potential vorticity, and with Scott McDowell and Tom Keffer, set about creating them. Surprisingly, the quantity turned out to be very mappable, using standard hydrographic data, and full of interesting structural patterns.

The idea of potential vorticity dynamics pervades many aspects of general circulation. It leads to diagnosis of hydrographic observations to estimate velocity (in a procedure known as the beta spiral), mapping of water masses, signatures of ventilation from the sea surface, mixing and forcing, and recirculation and mesoscale eddy mixing by the great circulation gyres. It also provides important constraints for predictions based on theoretical and numerical models. What makes this exotic quantity so likeable is that under ideal circumstances it is conserved in the moving fluid—like a colored dye, it reveals both the history of the flow and much about the current velocity and mass fields of the ocean, and it is the central "field variable" of interest in theoretical models.

The diffuse atmosphere acts like "expansion fluid" in this great heat engine.

We have touched on the ocean's forcing by the atmosphere, and the ocean-atmosphere interdependence in determining global climate. The diffuse atmosphere acts like "expansion fluid" in this great heat engine, while the ocean is a great heat reservoir, in a sort of thermal flywheel. The ocean and atmosphere exchange both thermodynamic and mechanical properties. Indeed, one exciting challenge in ocean dynamics is to describe how the combined effects of wind and "heat-salt-ice" dynamics works. But beyond physical interactions, ocean dynamics bears an intellectual relationship to atmospheric dynamics. Even if the two fluids were not connected, the shared presence of Rossby waves, instabilities, internal waves, mixing, and turbulence would be worth common study. In our teaching and research we ignore the "other" medium only at our peril.

The Coming Decades

The detailed physics described above may give some feel for what we do. But it does not give a sense of the *whole* of physical oceanography. I think that this vision is sorely lacking, and needs to be confronted if we are to approach the work of the 21st century. Just as exciting as the movements, transports, and exchanges within the ocean are the many relationships of ocean physics with the chemistry and biology of the seas, and the combined action of ocean and atmosphere to form global climate.

It is popular these days to talk about science moving from the era of Descartes's mechanical universe to the era of interactive systems. This appears, for example, in Fritjof Capra's popular philosophy book *The Turning Point* (and its movie clone *Mindwalk* starring, perhaps stretching our imagination, Liv Ullman as the physicist). The clock-like universe whose individual parts are perfectly understood in isolation, is now giving way to the System (so that a tree is a photosynthesizing haven for creatures great and small, a gas and nutrient pump, and an influence over weather and climate rather than a sum of mindless pieces). While this kind of thinking threatens to obscure the role of basic underlying dynamics, it does have some useful elements.

James Lovelock's Gaia (for example, *The Ages of Gaia*, W.W. Norton, New York, 1988) is the goddess whose biological sensibilities create one Earth, in which life is center stage, controlling (or at least strongly interacting with) chemistry, physics and, yes, even geology. No longer does the spectrum of life in Gaia do this to optimize Her comfort, according to the global evolutionists, but the control is there even though inadvertant. The old ghost of climate, in which physics and radiation more or less run the show, and biology evolved in a physically set environment, has paled away. With or without the mystic element biological and chemical influence on the physical world is undeniable.

It must be said that exciting discoveries are now on record in global geochemistry, biology, and climate. The El Niño-Southern Oscillation saga surely ranks high in the annals of far-reaching science; ice-age records from deep-sea sediments and ice sheets do the same. Yet where is our physics in all this? While enjoying our own excitements over oceanic fluid and thermodynamics, have we not been minding the rest of the store? Routinely, the paleoclimate debate is carried out with strong invocation of physical ocean processes (that's good), yet physical oceanographers, with their hard, rational approaches have not been heavily involved in these very issues (that's not good).

The general circulation models now being run furiously to demonstrate global climate hiccoughs and plankton blooms are "thought models": The physics of many processes is either poorly represented or completely absent. Society needs and wants these models, but so far we can't provide a useful owner's manual.

The 21st century is bearing down rapidly upon us. Where will it take us as a scientific community? There is remarkably little discussion about this immediate future (who knows even how we will even *pronounce* the year 2001?). With some 100 million more people in the world each year, global overpopulation—the mother of environmental problems, one might say—is likely to engulf us. Natural scientists rightly warn of global warming, ozone holes, pollution, and habitat destruction, all ominous side effects of the steeply growing population and affluence curves.

Global overpopulation—the Mother of environmental problems, one might say—is likely to engulf us.

The accelerating rate of change of our world, in all respects, will force new modes of research. A negative effect is the scourge of government demands for a five-year payoff from scientific research. One hears these loudly in Australia, England, and more recently, in the US. Frank Press, in his presidential address at the National Academy of Sciences this spring, emphasized science's role in national economic competitiveness. The word *environment* was mentioned but once, and it was a long address. Some would question our narrow measures of economic health. Canadian environmentalist David Suzuki talks about the madness of these measures, by which Canada and Australia are ranked as economic basket cases and Japan an economic miracle—yet Canada and Australia are rich in natural resources while Japan has few. If, in terms of the *Bulletin of Atomic Scientists* atomic clock, nuclear weaponry threatens our

existence, then exponential economic growth must surely be the second of the major forces driving us to the "edge of midnight."

These developments demand that we plan our future as physical oceanographers with a nearly impossible agenda: Follow the logical thread of physical oceanography into uncharted, interactive problems involving the changing ocean, atmosphere, and biosphere; be prepared increasingly to give good answers to tough questions about the systems' response to environmental stress; and yet carry on the wonderful work of establishing the basic principles of dynamics. These ideas of wind-driven general circulation, water masses, mixing, waves, and air-sea transfer will, over time, provide the strength of predictive and interactive modeling. To give up these sharp tools would be to give up the ship.

The smallness of the physical oceanography community has, in the past, permitted us to lead lives of healthy diversity, thinking one month (or one moment) about the Gulf Stream and the next about mixing in the deep Pacific. Working against this is the faster pace of research and discovery, but working for it is the quality, high resolution, and global scope of many modern observations. It is easier to understand a good story than a bad, incomplete, or vague one. And, significantly, good observations seem inexorably to bring the investigator to grips with more important questions. No longer so worried about data coverage, one is free to relate data to basic dynamical questions.

Thus a happy ending would be for physical oceanography to rise to the challenge of complex interactions with biology, chemistry, and atmospheric sciences, and more actively provide models and insights as bases for understanding our changing natural world. It means joining summer courses in biogeochemical cycles, spending more time with unfamiliar groups of ice-age climatologists, atmospheric scientists, and population biologists, and adding more to an already crowded agenda of graduate courses. By continuing to develop basic dynamics, we can be empowered by simpler ideas and faster computers.

By continuing to develop basic dynamics, we can be empowered by simpler ideas and faster computers.

But with all of the shiny appeal of computer color graphics, it is crucial to remember that individual, often lonely, creativity and care are the greatest resources. These qualities describe well the careers of Henry Stommel and Joe Reid (recipients of the Alexander Agassiz Medal for oceanography, in 1979 and 1992, respectively). A student interested in our field could do worse than sit with their research papers for an afternoon, to see where simple curiosity about the natural world can lead.

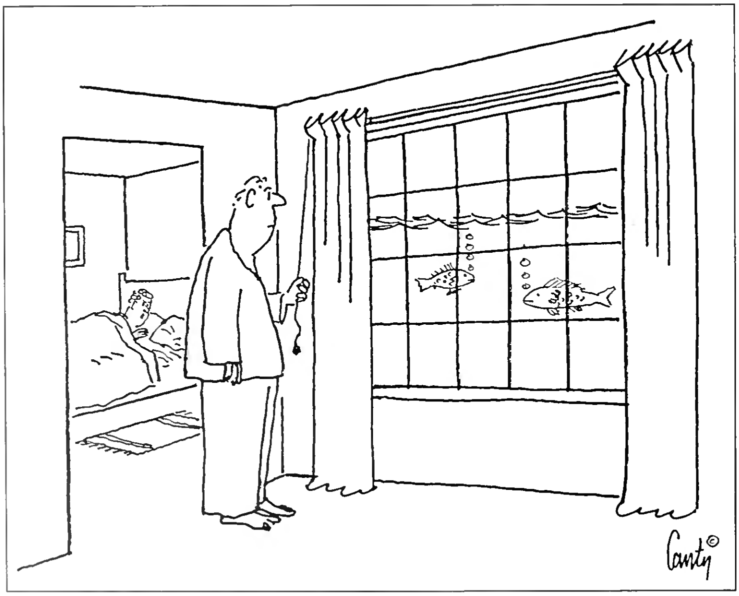
Peter B. Rhines has interests in ocean circulation, waves, atmospheric dynamics and climate. After 12 years at Woods Hole Oceanographic Institution, he wanted to help build oceanography closer to the center of university life, and moved to the University of Washington, where he is Professor of Oceanography and Atmospheric Sciences.

Focus on the Coast

Coastal Physical Oceanography

Kenneth H. Brink

The coastal ocean is different from the rest of the ocean. Physical processes occurring there are strongly influenced by the water's interaction with the coastal boundary and with bottom topography—the continental shelf and slope often drop off to depths of about 4,000 meters over offshore distances of 100 to 200 kilometers. Because water on a rotating planet such as Earth prefers to move as a column, water flow normally does not cross depth contours that would distort the column. Offshore flow, therefore, is very limited. Because of the lack of exchange, continental shelf waters are often distinctly different from those farther offshore. This is especially true where the shelf is wide and flat and the slope narrow and steep. Further, the topography itself, and the coast, through blocking effects, give rise to a number of boundary processes that simply are not found in most of the open ocean. This distinctiveness makes coastal-ocean study a subject essentially separate from open-ocean study.



William Canty/The Enterprise

"No, I don't want to look at the exceptionally high tide."

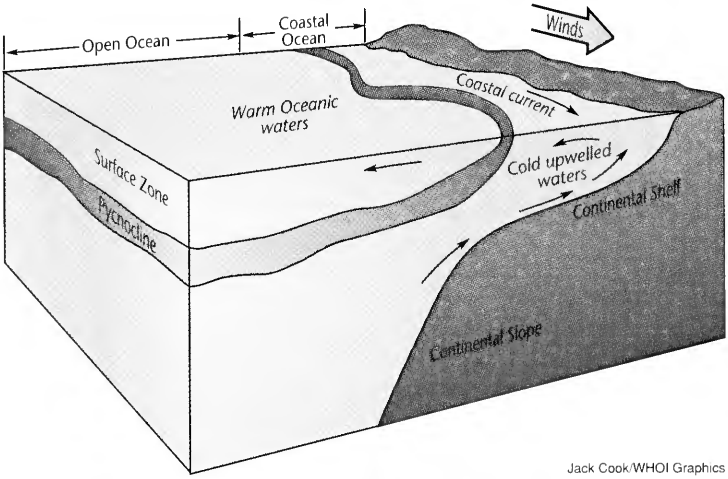
Some Coastal-Ocean Processes

Tides. Astronomical gravitational forces drive tides throughout the ocean. Tidal amplification is most evident in certain coastal regions where the topography of capes and bays causes water waves to resonate in much the same way that sound waves in an organ pipe do. For example, the topography in the Gulf of Maine-Bay of Fundy system is almost exactly one half a surface gravity wavelength long for a wave of the tidal period, and this causes extreme tides in this area. The resulting currents are particularly important over Georges Bank, where they cause turbulence that mixes the water column from surface to bottom, making central Georges Bank anomalously cool and high year-round in nutrients that feed the famous Georges Bank fishery.

Freshwater Outflows. The low-salinity water running into the ocean from land is generally less dense than salty shelf water, and the difference in density creates pressure differences that propel the flow. Typically, fresh water "turns right" on leaving its estuary, then hugs the coast as it flows alongshore. This arrangement can be strongly modified, or even overpowered, by such effects as wind. Nonetheless, in some high-latitude regions where precipitation is especially heavy, such as along the coasts of Norway and the Alaskan panhandle, currents driven by freshwater outflows predominate.

Wind-driven Currents. Wind driving, like tides, is important throughout the world's oceans but is especially significant (and observable) in the coastal ocean. Wind driving occurs because the coast interrupts the near-surface (upper 10 to 30 meters) flow, which is directly influenced by wind stress. To compensate for this interruption, an additional flow forms, primarily alongshore. Since waters over the continental shelf are so shallow (typically less than about 200 meters), the compensating flow is concentrated over a shallow depth range, and is easy to observe. When winds and Earth's rotation combine to cause offshore flow near the surface (for example, southward winds along the US West Coast), cold, nutrient-rich deep waters are brought to the surface by the compensating flow. This coastal upwelling greatly enhances biological productivity in surface waters and often leads to important fisheries. In a particularly interesting aspect of coastal currents, the shelf-slope topography acts as a wave guide for slowly varying disturbances that propagate alongshore. This extends wind-driven current systems alongshore, so that currents along one stretch of the coast might be responding to wind fluctuations hundreds of kilometers away.

Some common themes arise in coastal oceanography. First, the coastal boundary and shelf-slope topography tend to strongly influence nearly all aspects of water flow. Second, in the coastal ocean, atmospheric forcing, in the form of winds and heat fluxes, is extremely important and often leads to highly visible effects. Therefore, our limited knowledge of coastal meteorology is a serious roadblock to understanding the coastal ocean. Finally, there tends to be close coupling of the problems of the different oceanographic disciplines: Aside from physical controls on biological processes, coastal currents govern sediment transport processes, and, coupled with biological and geological processes, strongly influence chemical distributions.



Jack Cook/WHOI Graphics

Wind-induced upwelling occurs when winds and Earth's rotation move surface water away from the shore. Deeper, colder waters from the pycnocline (100 to 200 meters deep) shift upward, replacing the surface waters. This upwelling is common in coastal regions, along the eastern boundaries of ocean basins.

The strong linkages between the problems of the various coastal-science disciplines make problems in the nearshore region complex and interesting. Addressing these problems, with their considerable societal implications, calls for coordinated interdisciplinary research efforts. These efforts are beginning to materialize in the form of major scientific programs such as GLOBEC (GLobal Ocean ECosystem Dynamics) and especially CoOP (COastal Ocean Processes).

Kenneth H. Brink is an Associate Scientist in the Physical Oceanography Department at Woods Hole Oceanographic Institution and is currently serving as Chair of the CoOp (Coastal Ocean Processes) steering committee.

Creature Feature

Travelers in the Empty Blue

Francis G. Carey

The blue shark (*Prionace glauca*) is found throughout the world's oceans and is the most common large pelagic predator in northeastern US waters. Usually 6 to 9 feet long, this slender shark has large pectoral fins, and swims in a graceful, sinuous fashion. The underside of the shark is white, but its dorsal surface is a rich blue color with electric blue highlights, hence its name. Its diet consists mostly of fish and cephalopods, but unlike other fish eaters its broad teeth are serrated blades suited to cutting chunks from larger prey. When feeding on large animals, the blue shark does not chew, but, using powerful tail strokes, it spins and twists its body so that its teeth saw out large chunks of meat. Dead whales found floating at sea are often surrounded by blue sharks, but divers find these sharks cautious, hesitant beasts that may circle and circle, yet rarely attack.

Blue sharks depart northeastern US inshore waters in late fall and return the following spring. Their migration has been investigated in tag-recapture studies. Since 1963 there have been more than 1,700 tag returns in the National Marine Fisheries Service Cooperative Tagging Program. Tagged sharks have been recaptured throughout the Atlantic, including the waters of Europe, North Africa, and the Caribbean. Their migration is not channeled, like geese along a flyway, but appears to be a broad clockwise movement around the Atlantic Basin.

In common with many other sharks, blue sharks show geographic segregation of sexes. They appear to use the entire ocean basin in their reproductive cycle. Adult males and juveniles of both sexes appear off northeastern US shores in late spring and early summer. After mating, young females are conspicuously covered with bites; this appears to be in the order of things, as females are equipped with dorsal skin nearly an inch thick, compared to about a one-quarter inch on males. Immature females can store sperm for a long time, perhaps years, before using it to internally fertilize their eggs. Pregnant females are rare in the western North Atlantic, but more common in the eastern part of the ocean where they may bear 20 to 40 pups in somewhat protected regions such as the Bay of Biscay, where mature males are not found. The sexual segregation may serve to reduce predation on the young by the adults.

Though the blue shark is a large, powerful, streamlined animal, it swims slowly, usually at speeds between 0.5 and 1 knot. Occasional speed bursts up to 4 knots last less than a minute or so. Doubtless these sharks can move faster, but they rarely do. In swimming, a blue shark's tail beats slowly in a back-and-forth cycle that takes two to three seconds. By attaching small acoustic transmitters to the sharks we are able to follow them for periods of several days. These shark-tracking experiments show that sharks move in a manner suited for long distance travel: They swim continuously, and can maintain constant headings both day and night. The time scale of a seasonal migration is measured in months, and while they swim slowly, steady swimming can take them thousands of kilometers in a season. Food is not abundant in the central regions of the Atlantic, so an energy-efficient mode of swimming and a store of reserve fat in the liver are probably important in these journeys. Their streamlined bodies and slow movements must minimize the energy required for their travels.

As they swim along, sharks move up and down through several hundreds of meters of depth in a cycle that may be repeated every few hours during the day. Sharks are olfactory predators that live in a horizontally stratified environment where odor trails spread laterally. The up-and-down movements may be part of a hunting strategy that allows them to search many strata for prey. The vertical excursions, which may go as deep as 600 meters, take the animal through a large temperature range, as much as 19°C every few hours. The blue shark is a cold-bodied fish whose body temperature follows, in a delayed fashion, temperature changes in the water. When it leaves the warm surface water for the cold below the thermocline, the shark's muscle tissue cools slowly and remains significantly warmer than the water for an hour or so. On returning to the surface it rewarms rapidly, two to four times faster than it cooled. By moving up and down, the shark can use heat acquired at the surface to remain warm in the cold depths. This behavioral thermoregulation may be another reason for the shark's up-and-down swimming pattern.

Their electrosense allows sharks to detect electric fields that are generated by ocean currents. Sharks may speed their progress and reduce the energy required for travel by following the currents of the North Atlantic gyre. While intuitively this would make sense, at present we cannot prove that they are actually following favorable currents. The tag-recapture program reveals shark travel times between two geographic points, but yields no information about the paths taken between release and recapture. The shark-tracking experiments with acoustic transmitters are limited in duration to a week or less by the need to physically follow the fish, and are too brief to describe migration. Satellite tracking may offer an opportunity to obtain long-term, detailed records of the actual courses followed and speeds of movement over a period of months. Although the radio signals that link to the satellite will not penetrate seawater, the blue shark's habit of coming to the surface several times each day, often with its fins out of water, may permit such transmissions. If satellite tracking is successful, we will be able to compare the shark's course with that of prevailing current systems and with currents inferred from remote sensing data.

Harold Wes Pratt/Marine Biological Photography

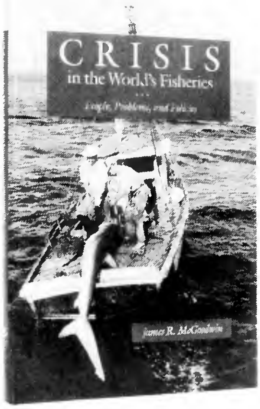
The blue shark gets its name from the rich blue color and electric blue highlights of its dorsal surface. The animal's migration, investigated in tag-recapture studies, appears to be a broad clockwise movement around the Atlantic Basin. Scientists suspect that the sharks may speed their progress and reduce their energy required for travel by following the currents of the North Atlantic gyre.

Sharks are an ancient group that evolved effective ways for "doing that which needs to be done." Their problems and solutions, however, may be beyond our land-based experience and difficult for us to imagine. We have some fascinating opportunities to learn more about the lives of these far-ranging animals.

Francis G. Carey is currently a Senior Scientist and claims to have been at Woods Hole Oceanographic Institution since the late Pleistocene.

Book & Video Reviews

Crisis in the World's Fisheries



By James R. McGoodwin, 1990. Stanford University Press, Stanford, CA; 235 pp. - $35.

There are new reports daily on the sad state of the world's fisheries. National compilations suggest that many stocks are depleted regionally and nationally. Fish like the coho salmon that once were very abundant in the Pacific Northwest have been reported as endangered. Other species, including bluefin tuna, have been described as being in danger of extinction. More than 20 books have been written that deal with the management and status of marine fisheries. McGoodwin discusses in depth the nature of the historical world fisheries and their present status in his book. He paints a picture of an industry in trouble.

McGoodwin describes the commercial fishing profession and discusses its practitioners, called *fishers*. He emphasizes that modern methods of fishing—including the large factory ships, associated trawlers, and massive trawling gear—have been instrumental in providing the overharvesting capacity that has reduced the world's fisheries to their present state. He notes that generally the fisheries are neither publicly owned nor privately represented; consequently extensive modernization of the world's fishing fleets has resulted in a surplus fishing capacity. In turn, this has resulted in a significant change in the life of the fishers.

Although fisheries research biologists have for decades predicted a continuing downward trend in most of the world fish stocks, any way out of the dilemma has been most difficult to formulate and even more difficult to implement. While this book takes a somewhat anthropological point of view, the author does describe the concepts of *maximum sustained yield* and *maximum economic yield* in an understandable manner. His narrative discusses the economics of current fisheries and management endeavors that have been put into place. McGoodwin emphasizes the irrationality of marginal fishing and develops a strategy that he believes might turn the situation around. Using case studies of the fisheries from throughout the world and drawing from his personal studies, he proposes short- and long-term plans and management activities. In doing this he touches upon limited entry, effort control, and catch limits, with philosophical attention to the concept put forth earlier by Hardin, in *The Tragedy of the Commons*.

Considering how primitive fishers operated to avoid overfishing, McGoodwin suggests that modern fishers can manage their own endeavors in a similar way by operating within regional or local environs. Earlier fishers tended to work within the limitations of the stocks themselves, harvesting what they needed to feed themselves, their families, or local economies. They were often part-time fishers, who combined land-based activities with fishing to provide the total sustenance required for their own individual well-being. Most important, they depended upon relatively primitive gear, smaller vessels, and efforts dictated by weather conditions, which regularly prevented them from moving far afield or conducting fishing over long periods.

In reviewing case studies from the Americas and the Orient, McGoodwin develops a theme from which a single characteristic of all primitive fishers emerges: the ability to maintain certain "property rights" over fishing grounds. He relates this "indigenous management" to the concept of biological controls.

In later chapters, the author points out a need for communication or "networking" between the fishers, fisheries managers, and the general citizenry. Environmental issues are not emphasized, but he notes that what happens on the landmass affects coastal and shelf fisheries, and suggests that taxes or rents be charged to businesses or individuals whose activities pollute the waterways. Pointing out politics in modern fisheries, he emphasizes that the political process tends to dominate, often clouding needs for adequate fishery management. In developing such arguments, McGoodwin provides examples of "cooperative management" regimes in Iceland and Norway. However, he does not point out that these regimes are successful because of long traditions of socialism and cooperation. In considering mariculture, he never deals with the complexities that might evolve as mariculture production begins to interact with the traditional fisheries and other uses of the coastal zone—shipping, tourism, minerals, and recreation.

Crisis in the World's Fisheries is good reading for those people involved with fishers or the economics and management of the industry. While not delving far into the complex biological and ecological aspects of fishery stocks, it provides an overview of the industry, especially as it has evolved from sociological and economic points of view. When read along with recent treatises on fisheries and fisheries management, it provides insight into the nature of the industry and possible solutions that might be implemented in the future. If it has one shortcoming, it is that it does not attempt to reach out to the future to see what the world might look like once there are 11 billion people on the earth, with many more individuals seeking their protein from the seas.

—Dr. John B. Pearce
Deputy Center Director
Northeast Fisheries Science Center
National Marine Fisheries Service

Ecology of the Coral Reef

By Films for the Humanities and Sciences, 1991. Princeton, NJ; 28 minutes - purchase $149/rent $75.

How eagerly I had looked forward to reviewing *Ecology of the Coral Reef* in hopes it might be informative and useful to my work. I have spent the better part of the last decade trying to communicate to people what I know about coral reefs. I need all the help I can find. So do corals. Reefs are beautiful and important, but human activities are contributing to a rapid decline in their health all over the globe. A good documentary on coral reefs is sorely needed; it would be both timely and valuable. *Ecology of the Coral Reef*, however, is disappointing. Shocking. Preposterous. Bad.

This Man and the Biosphere film fails abysmally to communicate about all three of these pertinent aspects of corals: their beauty, their importance, and the man-made threats to their survival. How can this be? Recent and good underwater video and film footage is readily available, whether from reefs in the Caribbean or the Indo-Pacific. I know; I have looked for it recently and found it. Numerous well-informed scientists are also readily available for consultation and data. I know; I have talked with them and read their reports. There really is no excuse for this failure.

Why does this documentary fail? Although 25 minutes long, less than one fourth of this time is actually devoted to coral reefs. Less than six minutes from the beginning, this so-called coral reef film abruptly turns from corals to focus on the shores of the Mediterranean, and the rest of the film is devoted to describing the seaweed and the seaweed habitat there. Worse still, in the short initial portion that actually does pretend to address coral, the narration just does not match the footage. The introductory aerial shots show an anonymous and calm emerald green sea, without a reef or a wave in sight, but accompanied by the statement that reefs protect coastlines from erosion caused by crashing waves. Subsistence fishing and the reef as a "secret underwater garden" are mentioned next. But, improbably, the footage shows tourists, from above-water only. The tourists bend over awkwardly to put on fins, they wade down a cement ramp, and they bob and snorkel en masse. Next, a statement mentioning damage to reefs by sediments is teamed up with what looks to be a pristine river passing through a mountain forest. Even in the lengthy mid portion devoted solely to the Mediterranean (where there are no coral reefs), the words still do not match: "Airports" are mentioned with a dock scene, "dynamite" with the side of a boat, "heavy metals" with a shoreline and then a tanker, and "public education" with a castle. This frustrating style continues to the bitter end, which delivers the disheartening conclusion that sea levels may be rising, perhaps as much as 3 feet, with the rise in global temperatures. Although perhaps just cause for concern, the final scene is merely one of a sunset, waves tossing onto a rocky coast.

The biggest disappointment of all is that the footage is so terrible. It is old. It is uninspiring. In the just over two minutes of underwater views that pertain to coral reefs, most scenes, apparently shot in an aquarium tank, were of what appear to be fake corals. Descriptions of the natural history of corals are accompanied only by shots of the tentacles of a sea anemone! There are no close-ups of coral polyps, which would help viewers understand the structure of these fragile animals. Instead, nearly one minute of the two is devoted to the predatory starfish, the Crown-of-Thorns; but only its thorns, never a whole animal, come into view. The tank scenes are all shadowy and dark, finally and unmercifully relieved by just a few (23!) seconds of shaky footage showing a distant, bluish, and blurry live reef.

Watching this film, not to mention writing a review about it, has been a dreadful waste of time. Not only do I regret the time that I have thrown away, I lament the amount of time and money that has been wasted producing and marketing the film. Time races on, and environmental conditions worsen. People, especially children, are concerned and eager to learn. That *Ecology of the Coral Reef* might reach a general audience is especially disturbing, because it risks dampening interest and enthusiasm for studying life in the sea. All of us—whether scientists or filmmakers, writers, teachers, or artists—have a heavy responsibility to communicate what we know best about life on our planet, as best we can. This video falls abysmally short.

—Katherine Muzik
Associate
Museum of Comparative Zoology
Harvard University

Enjoying a Life in Science: the Autobiography of P.F. Scholander

1990. University of Alaska Press, Anchorage, AK; 226 pp. - $22.95.

Pete (Per Fredrik Thorkelsson) Scholander (1905 to 1980) was a man who approached both life and science with curiosity, enthusiasm, and wit. His well-written autobiography reflects the ebullient personality of the man I was privileged to know. My first voyage out of Woods Hole Oceanographic Institution (WHOI) was in the summer of 1952, a few weeks before I joined the institution staff. William C. Schroeder invited me to go as his assistant on a deep-sea trawling cruise on the chartered Woods Hole dragger *Cap'n Bill II.* It was a week of high excitement and learning for me. I was helping a man famed for his knowledge of ocean fishes, saw a rich, deep-water, benthic ichthyofauna that was wholly new to me, had instruction and laughs from the boat's skipper Henry Klimm and his skillful and lively crew, and last and by no means least, began my friendship with Pete Scholander. He was a handsome, energetic, charming, irreverent man, quick to laugh and smile. He had a quizzical expression and the remnants of a Scandinavian accent, and though generous, was somewhat arrogant.

Using one of a series of microanalyzers that Pete had invented, he and the man helping him, Levie van Dam, were studying swim bladder gases in the fishes that the otter trawl hauled up from 1,000 meters. This was part of Pete's discovery and elucidation of counter-current exchangers by which plants and animals move gas, heat, and other things against adverse gradients.

As I sorted and pickled fish and their stomach contents, I kept an ear cocked in the direction of Pete's little on-deck lab, from which was coming some remarkable talk, often humorous and earthy, if not vulgar. (Attributing the line to the Swedish playwright August Strindberg, Pete told me some years later, "A dirty mind is a permanent feast.") One of the things I learned was how indispensable to physiologists a certain very personal item was. It seemed that every follow-up experiment they meant to do upon getting back to Woods Hole utilized these semipermeable membranes:

> *van Dam*: Take a thistle tube and stretch a condom over its mouth; then....
> *Scholander*: Better yet, take two condoms; to the second one attach....

Pete seemed to know something (often a lot) about almost everything. One brilliantly clear evening over the continental slope off southern Nova Scotia, when the setting sun was nearing a knife-sharp horizon, he said, "I think we'll see the green flash tonight." What is it about those two words that invariably elicits suspicion from every first-time hearer? I can still see van Dam snatching off his dark glasses too late when the rest of us exclaimed softly a few minutes later. (We were all serious watchers the next night and saw the phenomenon again.)

One of the amazing creatures that we dragged up in plenty on that cruise was the huge deep-sea crab, *Geryon quinquedens*, a bright red fellow even uncooked that might stretch a couple of feet from tip to claw tip. Pete mused, "I wonder what they taste like?" We set aside a couple of fish baskets filled with the crabs, covering them with pieces of wet burlap. Back in Woods Hole, Pete and his beautiful wife Susan cooked them up, and I discovered that food and drink was another part of the world for which Pete had a great enthusiasm. It happened, while the crabs were boiling, that a Brahms violin concerto played on the radio; Pete grabbed his own instrument from atop the piano and played along. Later, I heard him say about the *Geryon* (and later still about many other things), "It was so good I cried with every bite!"

Pete grew up in Sweden, son of a Swedish father, an engineer, and Norwegian mother, a musician. Natural history was his early passion; he trained as a physician, but along the way was diverted repeatedly by lichens and other plants, and in 1934, two years after graduating near the very bottom of his medical school class, was awarded a Ph.D. in botany based on his plant explorations in Greenland and Svalbard. In the same year and with another course change, he began studying diving in birds and mammals at the University of Oslo.

In 1939, Pete joined diving physiologist Laurence Irving at Swarthmore College. Irving was not only mentor and colleague, but a dozen years later became Pete's father-in-law. In 1943 both Irving and Pete were given commissions in the air corps where they evaluated survival equipment and other gear. Out of an Alaskan air base, Pete and two others who had never jumped before parachuted in winter onto a downed aircraft and saved three survivors. Narrowly averting court-martial, Pete got a medal instead.

In 1951 he and Susan, married for a few months, settled in Woods Hole, where they were to spend only about three years. Pete studied swim-bladder function in deep-sea fishes (as already noted), supercooling in Arctic ones, and the rise of sap in tall grapevines. The last (as well as some other examples of his catholicity) caused some critics, including Columbus Iselin, then WHOI director, to question Pete's devotion to oceanography. Pete left WHOI and was welcomed as Professor of Physiology at Scripps, where he spent the rest of his career. While at Scripps, he was the prime mover in seeing *Alpha Helix*, the NSF vessel for experimental biology, designed, launched, and used.

Acclimation to cold by Norwegians, Lapps, Eskimos, Australian aborigines, and Fuegian Indians; ancient atmosphere in Greenland ice; bradycardia in Queensland pearl divers; and sap rise in mangroves were only a few of the things Pete studied. He never missed a chance to go to some strange place to look into some seemingly impossible feat by a plant or animal. And wherever he went he made new friends, sampled the local specialties of food and drink, and celebrated life in general. A "purer" scientist perhaps never lived. Pete lives again in this lively, well-written book. Since reviewers are supposed to be critical, I will say that the index is not as good as the rest of the book.

—Richard H. Backus
Scientist Emeritus
Biology Department
Woods Hole Oceanographic Institution

Books & Videos Received

ENVIRONMENT

World Resources 1992–93: A Guide to the Global Environment–Toward Sustainable Development. A report by the World Resources Institute in collaboration with the United Nations Environment Program and the United Nations Development Programme; 1992; Oxford University Press, New York, NY;
385 pp. - $32.50.

The Environmental Sourcebook: A Comprehensive, Up-To-Date Guide to the Environmental Movement by Edith C. Stein; 1992; Lyons & Burford Publishers, New York, NY; 264 pp. - $16.95.

Plastics Recycling: Products and Processes edited by R.J. Ehrig; 1992; Oxford University Press, New York, NY;
289 pp. -$64

OCEANOGRAPHY

Ecology of Estuaries: Anthropogenic Effects by Michael J. Kennish; 1991; CRC Press, Inc., Boca Raton, FLA;
494 pp. - $139.95.

Guidelines on the study of seawater intrusion into rivers edited by H. vander Tuin; UNIPUB, Lanham, MD;
138 pp. - $25.

An Introduction to Marine Biogeochemistry by Susan M. Libes; 1992; John Wiley & Sons, Inc., New York, NY;
734 pp. - $45.95.

"Deep-Sea Food Chains and the Global Carbon Cycle—Proceedings of the NATO Advanced Research Workshop on 'Deep-Sea Food Chains and Their Relation to the Global Carbon Cycles," held in College Station, TX, USA, April 1991 edited by Gilbert T. Rowe; 1992; Kluwer Academic Publishers Group, The Netherlands;
416 pp. - £77.

Oxygen Dynamics in the Chesapeake Bay: A Synthesis of Recent Research edited by David E. Smith, Merrill Leffler, and Gail Machiernan; 1992; Maryland Sea Grant College, College Park, MD; 234 pp. - $24.95.

The Arctic Seas–Climatology, Oceanography, Geology, and Biology edited by Yvonne Hermen; 1992; Van Nostrand Reinhold, Florence, KY; 816 pp. - $92.95.

YOUNG PEOPLE

At Home in the Coral Reef by Katy Muzik; 1992; Charlesbridge Publishing, Watertown, MA; 28 pp. - $14.95.

The Beaver: The Animal Observed With Over 50 Photographs by Hope Ryden; 1986; Lyons & Burford Publishers, New York, NY; 63 pp. - $9.95.

Going Lobstering by Jerry Pallotta; 1992; Charlesbridge Publishing, Watertown, MA; 30 pp. - $15.95.

The Ocean Alphabet Book by Jerry Pallotta; 1992; Charlesbridge Publishing, Watertown, MA; 30 pp. - $14.95.

Snorkeling for Kids (of all ages!) by Judith Jennet; 1992; National Association of Underwater Instructors, Montclair, CA; 56 pp. - $8.95.

BIOLOGY

Assessments and Decisions: A study of information gathering by hermit crabs (part of a series of Studies in Behavioral Adaptation) by R.W. Elwood and S. J. Neil; 1992; Routledge, Chapman & Hall, New York, NY; 192 pp. - $69.95.

Protozoan Plankton Ecology by Johanna Laybourn-Parry; 1992; Routledge, Chapman & Hall, New York, NY; 231 pp. - $99.

Ecological Roles of Marine Natural Products edited by Valerie J. Paul; 1992; Cornell University Press, Ithaca, NY; 245 pp. - $39.95.

VIDEOS

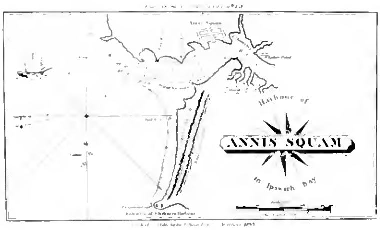
The Return of the Child: The Effects of "El Niño" produced by Films for the Humanities & Sciences, Princeton, NJ; 26 minutes, color; purchase $149; rental $75.

SPORT FISHING

Saltwater Gamefishing Offshore and Onshore by Peter Goadby; 1992; International Marine/McGraw-Hill, Blue Ridge Summit, PA; 342 pp. - $34.95.

Striper Surf by Frank Daignault; 1992; The Globe Pequot Press, Chester, CT; 249 pp. - $21.95.

The Inquisitive Angler by Ed Migdalski; 1992; Lyons & Burford Publishers, New York, NY; 221 pp. - $27.95.



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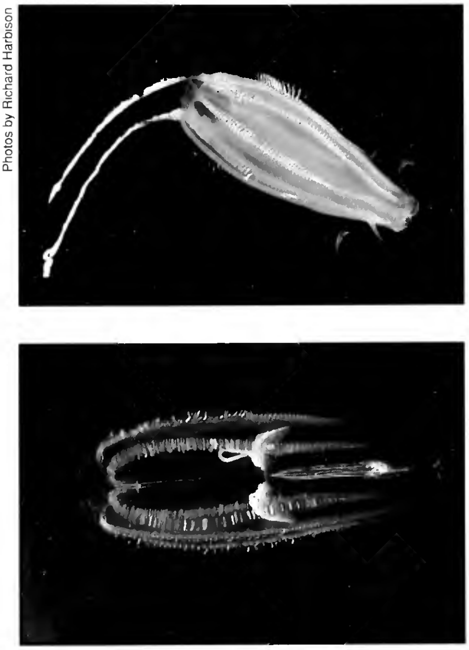
Photos by Richard Harbison

Biological Oceanography

Volume 35, Number 3, Fall 1992

With the Fall Issue, Biological Oceanography continues our 1992 series featuring four basic ocean-science disciplines. Subjects in this issue range from marine viruses to new molecular approaches to marine biological problems. Our authors discuss limits to primary production, the microbial loop, communication and environmental (as well as natural) threats to the large animals at the top of the marine food chain, and tracking large game fish and squid. Others provide a look at new tools for studying life forms in the ocean's interior, discuss the new wave of biological modeling, and describe "mixotrophic" species, deep-dwelling jellyfish (see photos), and animal/microbial symbioses. Don't miss these new insights to life in the world ocean!

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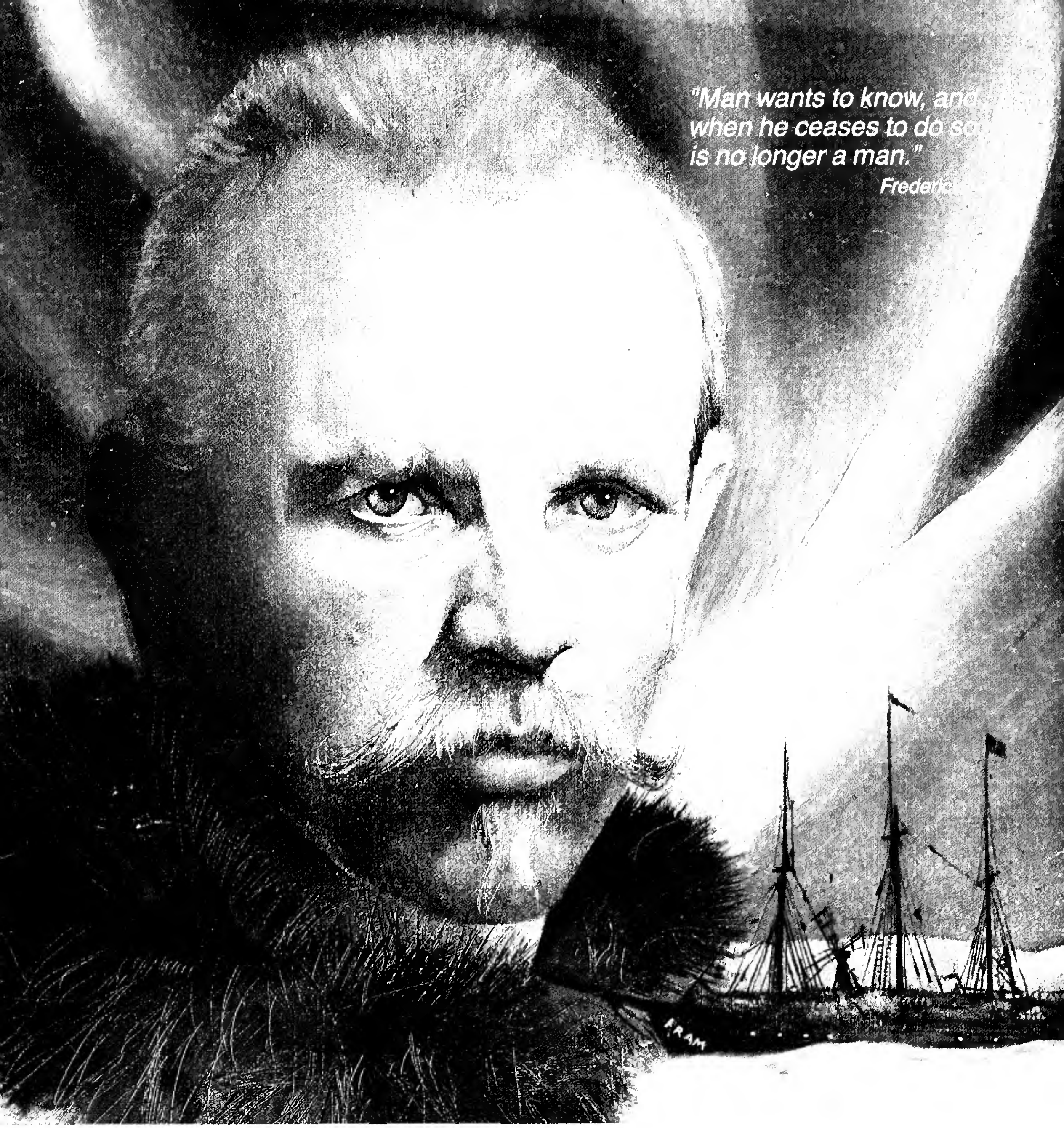
"Man wants to know, an
when he ceases to do s
is no longer a man."
Frederi
FRAM