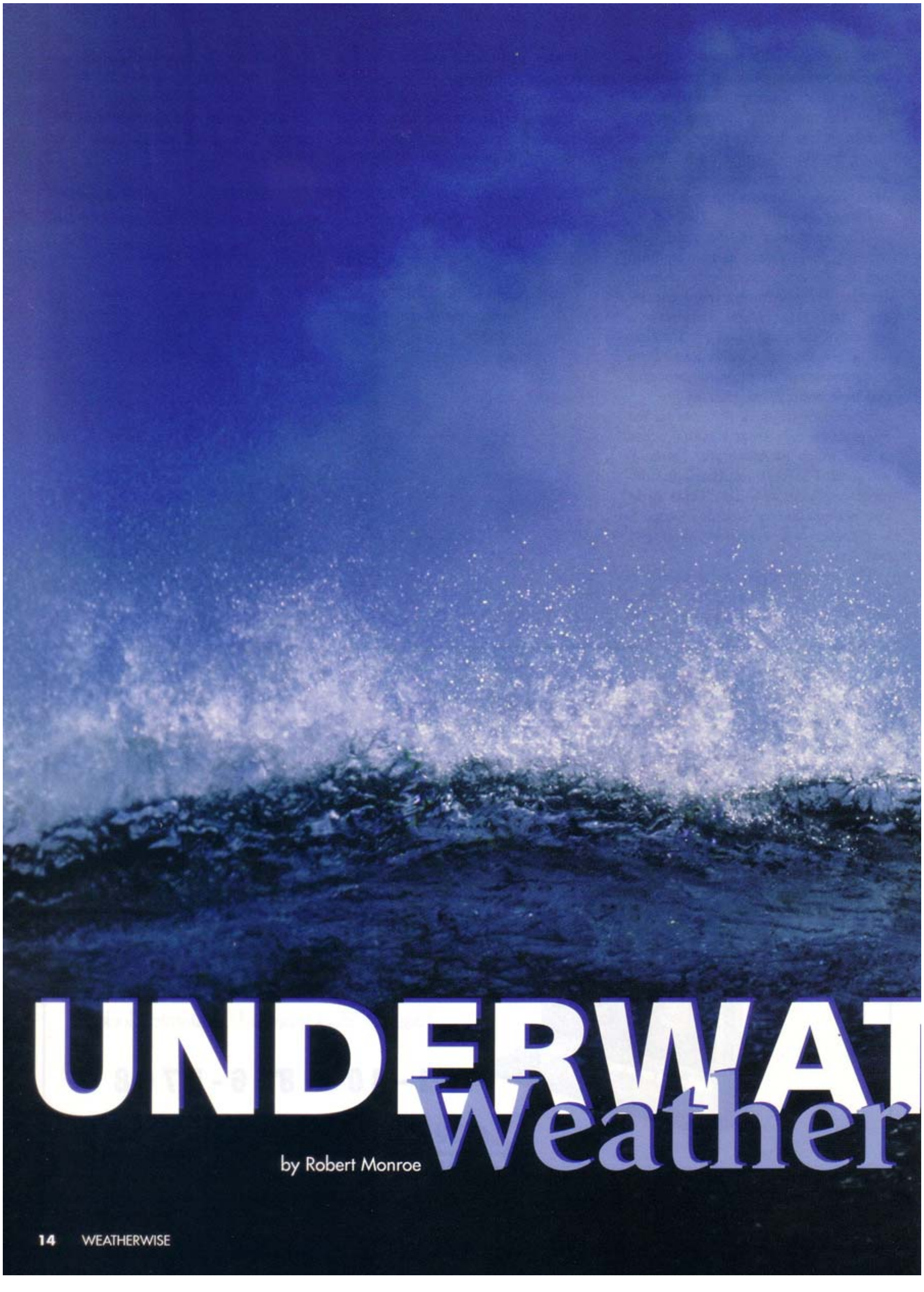
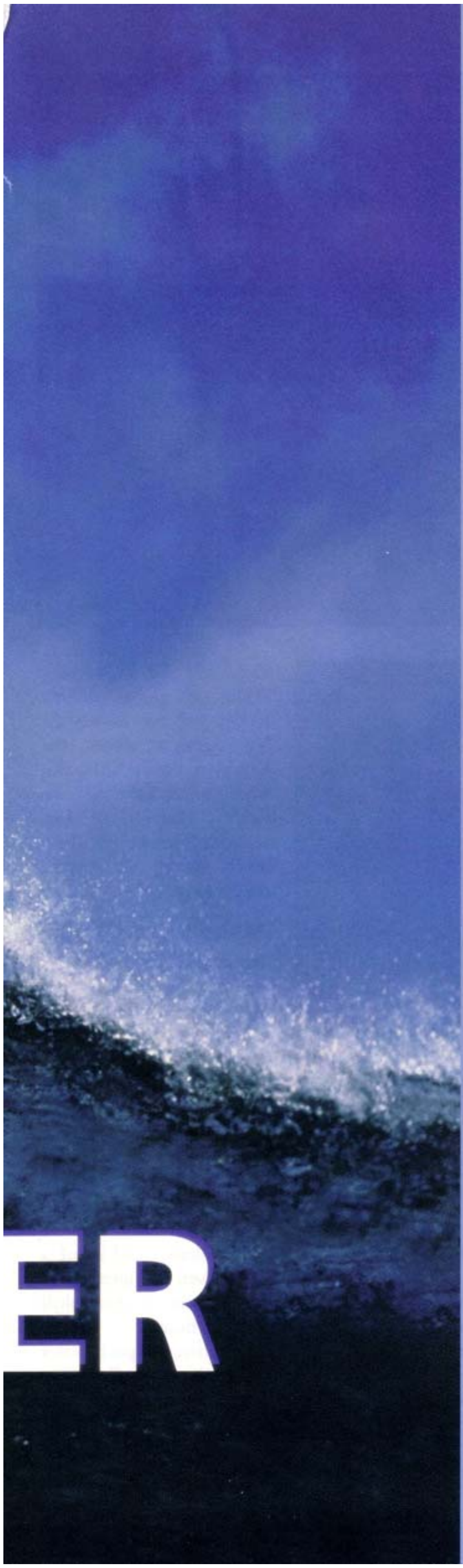


UNDERWAT Weather

by Robert Monroe



From liquid hurricanes to aquatic fronts, scientists seek to unlock the mysteries of oceanic weather.

For some scientists, weather is something they observe from the top down. They're part of a research community that studies fronts and hurricane-like eddies not in the sky but in the ocean.

It's a world of weather where "winds" of current, or "jets," are created by the clash of conflicting water densities; where swirling eddies resemble the rapidly changing patterns of cut-off highs and lows in the atmosphere but can spin for as long as a year; and where fronts are hubs of biological activity.

"Oceanic weather influences the distribution of phytoplankton, which other marine life feeds upon," says Dan Rudnick, a physical oceanographer at Scripps Institution of Oceanography in San Diego. "We don't care much about weather in the ocean in our own daily lives, but the fish certainly do."

As it turns out, underwater weather might play more of a role in our daily lives than we realize. It moves heat around the ocean and influences everything from coastal fog to El Niño effects that come to land. It helps push sea breezes onshore, adds to the formation of extratropical cyclones, and possibly creates decadal weather patterns across the Atlantic.

"Many scientists believe a significant amount of the ocean's heat transport occurs in fronts and eddies," Rudnick says, "so a better understanding of ocean weather may indeed improve our knowledge of climate."

ROBERT MONROE is a senior science writer for Explorations, *a quarterly magazine published by Scripps Institution of Oceanography.*

Right: Scripps oceanographer Dan Rudnick prepares to deploy the towed submersible SeaSoar to monitor temperature and salinity off the southern California coast.

Below: In this image of the northeastern U.S. coast, low biological productivity is indicated with blue and represents warmer waters. High productivity (representing colder water) is in red. The contrast in biological productivity reveals the Gulf Stream current and several warm-core Gulf Stream eddies.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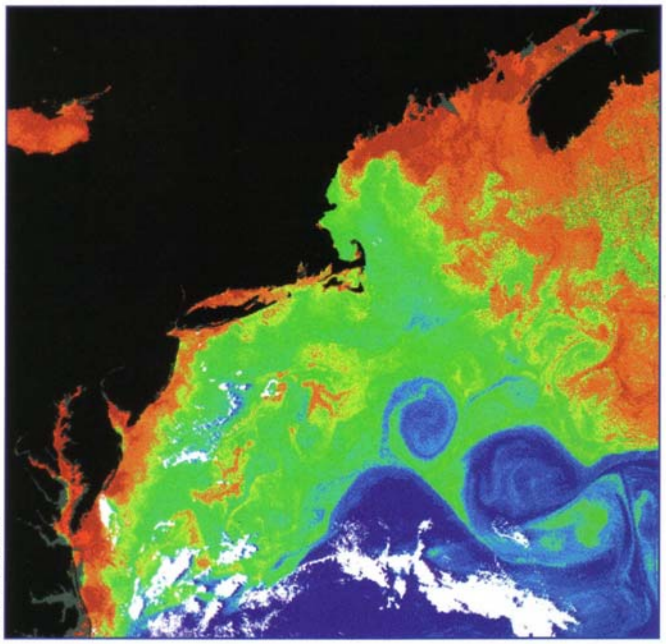
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This world was only barely understood before the past two decades, when advances like global positioning and thermal imagery from satellites let oceanographers see what was happening over ocean basins for the first time. Rudnick and other researchers are developing the next generation of instruments that will help science unlock the mysteries of ocean dynamics. These tools will fill in missing details of global climate models and may answer the big questions about the physics of oceans, including what some consider the field's "Holy Grail"—an accurate estimate of how much energy the world's oceans store.

At the Frontal Zone

Oceanographers don't classify oceanic weather features with the precision that their meteorological counterparts do. For example, they describe "fronts" as lines of rapid change between types of water. Often the difference is in the water's density—a function of its temperature and salinity—but sometimes differences in either of those factors alone could create a front. Even the interface of waters with different sediment or chlorophyll levels could be considered a front.

The division between different types of water at fronts is seldom a neat line. Usually a convergence of forces leads to the creation of eddies—swirls of current pinched off from the fronts much as cut-off highs are formed in the atmosphere. Resembling slow-motion, liquid

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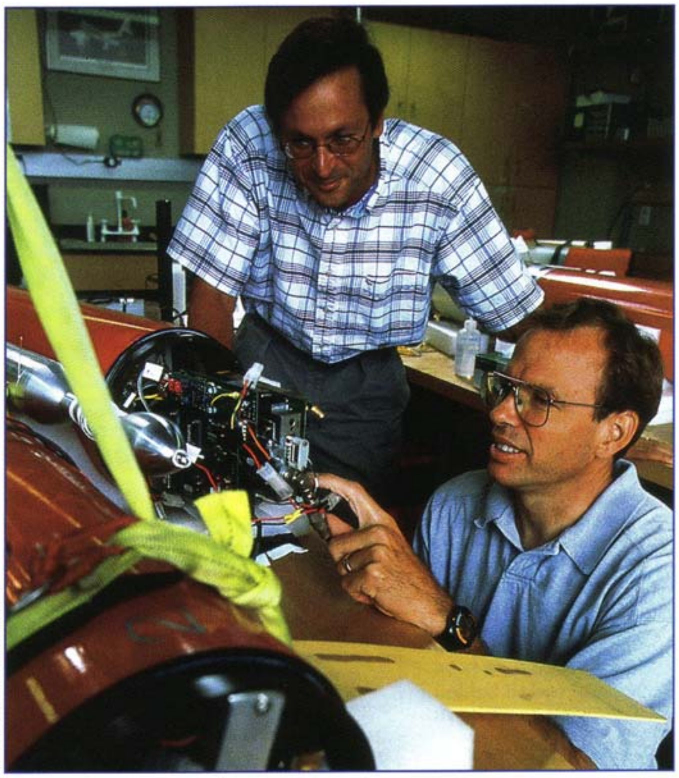
Left: SeaSoar is raised after a mission in the Pacific Ocean. These reusable submersibles are the workhorses that have helped refine ocean monitoring since the 1980s.

Below: Rudnick (standing) and colleague Jeff Sherman examine instruments inside Spray, a self-propelled glider in development that operates autonomously for months at a time and relays data back to the lab via satellite.



FRED GREAVES PHOTOGRAPHY

hurricanes, eddies can grow to as large as 60 miles in diameter.

Fronts in the ocean, such as the 1,700-mile-long Gulf Stream and its counterpart off Japan, the Kuroshio, form at the frontiers where traditionally warm and cool water masses meet. Some, like the subantarctic front, form a ring around the entire planet at its more southern latitudes where there are no continents to break them up.

Closer to the coasts, smaller fronts between 6 and 60 miles long form as the ocean encounters the topography of rising landmasses or river mouths. Many of these fronts, such as the Gulf Stream, are permanent features in the landscape of ocean weather, much like the jet stream that undulates across North America at the boundary between cold Arctic air and warmer air from the south. But many smaller, temporary fronts spawn eddies throughout the world's oceans at any one time, just as thousands of storms swirl in the atmosphere at any given moment.

Where the Action Is

Across the Scripps campus from Rudnick, biological oceanographer Peter Franks is more interested in how the ocean's physical aspects affect life there, and vice versa. The two scientists agree that the biological implications of fronts are one of the most important reasons to study them. While atmospheric fronts might send people scurrying indoors, their oceanic counterparts are where the action is for marine life.

Physical oceanography is like other fields of science in that many of its discoveries about fronts confirm information known intuitively for years by those who have needed to know it for their livelihood. For example, captains of fishing boats have long lived by a simple maxim: "Fish follow fronts." The captains follow the fish, looking for flotsam strands on the open ocean. Just as lines of dark clouds give atmospheric scientists visual clues to fronts in

The space shuttle is an excellent source for photos of undersea weather. Right: A chain of spiral eddies swirls off the California coast; Catalina Island is visible at left. Far right: Shears near coastal boundaries formed a string of eddies in the eastern Mediterranean Sea in 1984.

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SeaSoar may go the way of the dinosaur, as Rudnick hopes to replace cumbersome towed submersibles with this smaller, less expensive version, which can be deployed from and towed behind a small boat.

the sky, the convergence of flows at oceanic fronts churns debris to the surface to give a hint to fishermen. As Franks puts it, "It's because of weather in the ocean that we have sushi."

The correlation is so strong, notes another researcher, that Japanese weathercasters include the positions of oceanic fronts in their newscasts to help fishermen. U.S. fishermen can buy satellite imagery of fronts from select vendors.

"[In the United States,] it hasn't caught on with the same level of attention as in Japan, with the exception of yacht racers who recognize that this knowledge can and does win races," says Terry Joyce, a physical oceanographer at the Woods Hole Oceanographic Institution (WHOI) in Woods Hole, Massachusetts.

Other oceanographers note that mail carriers in colonial times got their transatlantic packages to their destinations more quickly using a basic knowledge of the Gulf Stream, possibly the most famous byproduct of what oceanographers call a front. Submarine commanders have relied on fronts for their survival even more directly than fishermen and other sailors. Starting in World War II, subs used fronts as shields from ship-based sonar, hiding in cold water under giant pools of warm water in the ocean. The density change refracted signals so that subs blurred into the background.

Navies learned to overcome that handicap, but to this day, there are gaps in our knowledge about how fronts form and what forces cause the accumulation of phytoplankton there. One thing oceanographers do know is that every weather phenomenon in the ocean is analogous to one in the atmosphere, a fact meteorologists know too.

"The similarities between various circulation systems found in both the extratropical atmosphere and ocean have been appreciated for some time," says Daniel Keyser, a professor in the Department of Earth and Atmospheric Sciences at the University at Albany, State University of New York.

Keyser, who studies extratropical cyclones, atmospheric fronts, and jet streams, notes a parallel between these phenomena and oceanic eddies. He says he follows the work of particular oceanographers who focus on the structure and dynamics of ocean weather. "We borrow and benefit from each other's theoretical and observational insights," Keyser says.

At Scripps, Rudnick looks at the horizontal structure of fronts and pores over observation-


PETER J. S. FRANKS, SCRIPPS INSTITUTION OF OCEANOGRAPHY

A Scripps research vessel transects a band of red tide off the coast of southern California. The band is caused when a bloom of the tiny red algae dies and is swept along the surface by an ocean current.

al data to determine their typical characteristics. He and his colleagues have borrowed a page from the meteorologist's handbook by using equations for the conservation of heat and momentum to derive thermal wind balance. This balance creates jets, the narrow currents at fronts that zip along at as much as two knots (2.3 m.p.h.). There are other dynamics at work as well, such as the Coriolis force, which, if unbalanced, creates rotating motions in the ocean, just as in the air.

How oceanic weather affects its counterpart in the sky is just beginning to be understood. El Niño is nearly universally believed to be the major force affecting atmospheric circulation over the Pacific, but it is unclear whether that dominance is repeated elsewhere. It is possible that Atlantic storms follow the Gulf Stream, for example, but the evidence just isn't there yet, says Joyce of WHOI.

A Matter of Scale

Weather in the ocean is taking place on a much smaller scale than its atmospheric counterpart but with larger consequences. Think of the ocean as a constantly churning layer cake of varying water temperatures and salinity levels from the surface to a depth of as much as 3,000 feet, an ocean region called the thermocline. Within that space, smaller, seasonal thermoclines form and dissipate. This is where the action is. Storms and winds actively mix the top layer, which ranges from tens to hundreds of feet deep, exchanging gases like oxygen and carbon dioxide between the air and the sea.

The adage "still waters run deep" rings true for oceanic weather. Whereas atmospheric conditions can change by the minute, oceanic weather patterns move in slow motion. Joyce has found, for example, that the Gulf Stream


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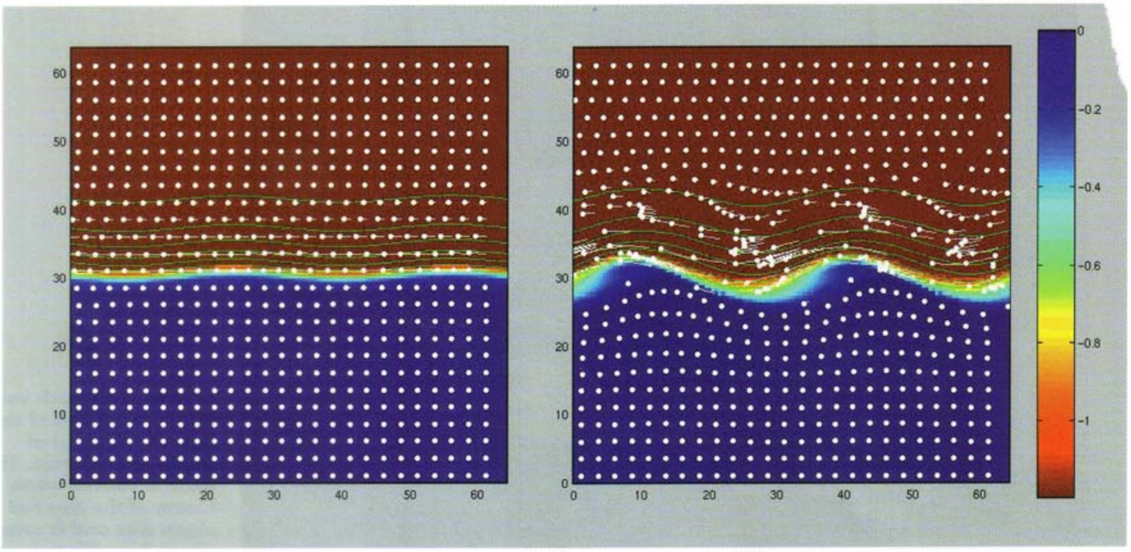
The entire Indian Ocean, Tasman Sea, and southwestern Pacific Ocean were covered with spiral eddies in this 1985 space shuttle photo. Data would later confirm that the eddies extended several hundred yards deep.



Above and opposite page: A series of computer-generated simulations shows the formation of eddies at an ocean front where waters of different densities meet. Small meanders in the front are magnified by water motion along the front, creating larger meanders, loops, and eddies similar to those formed in the atmosphere. The white dots represent particles at the surface such as plankton. Their "tails" indicate how far they've traveled in the last day. As with a surface-weather map, water-current speed and direction can be determined from these tails, and a jet can be identified by the fastest-moving particles.

routinely shifts north or south by as much as 60 miles over the course of a year and then, except for occasional frontal meanderings, stays put for years on end. Scientists aren't sure why this shift happens but suspect it could be caused by similar shifts in the jet stream overhead.

Fronts that form over time scales longer than a day and space scales longer than six miles would be able to spread unfettered were it not for the Coriolis force, which pushes the warm water mass clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Along coastlines, fronts form as part of another process called upwelling. As winds blow warm surface water offshore, colder water from below rises to take its place. Included in the cold water infusion are nutrients that phytoplankton need to propagate. The tiny well-fed organisms sometimes multiply in great enough numbers to color the ocean along fronts. Their predators show up to feast, as do *their* predators, and so on.

Temperature and salinity control the density of ocean water. Cold water is denser than hot water, and salty water is denser than freshwater. Sometimes fronts are hot and salty on one side and cold and fresh on the other so that the density contrast across the front is small. Compensated fronts like this have been the subject of much of Rudnick's work. Depending on their size, these fronts can last for weeks.

The two ingredients of density, temperature and salinity, are the direct counterparts of temperature and water vapor in the atmosphere. Oceanographers have it easier, however, because while water vapor can leave the atmosphere as rain, salt remains dissolved in the ocean.

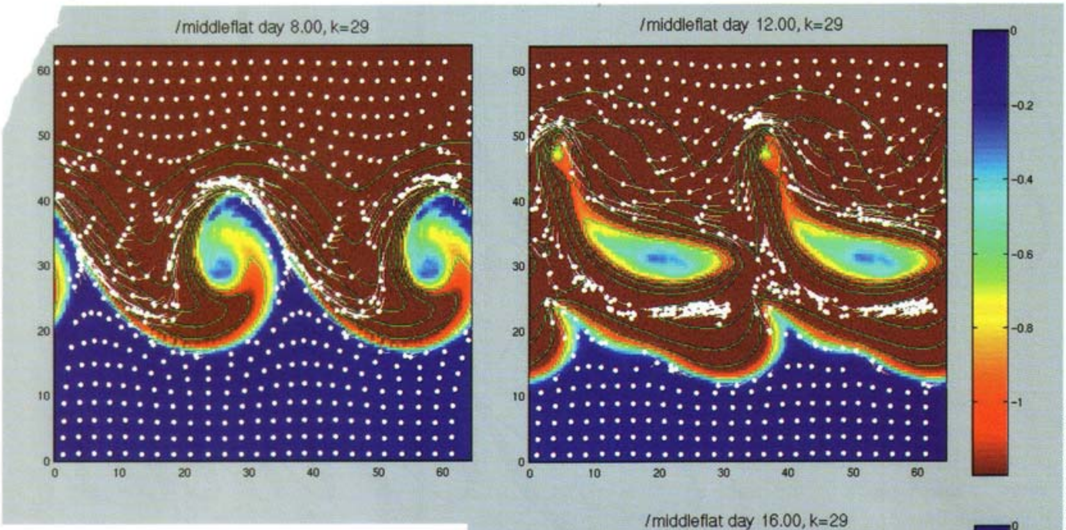
Similar Tool Kits

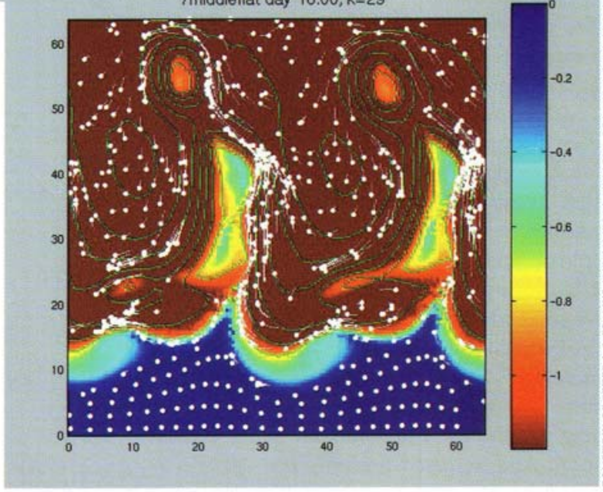
Perhaps because of the natural equivalents found between ocean weather and atmospheric weather, scientists have devised functionally similar devices to study both. Whereas meteorologists use radar, the oceanographer's "waves of choice," as Rudnick puts it, are acoustic waves.

Just as NOAA aircraft fly through hurricanes, underwater gliders are towed through the "storms" at oceanic fronts. Just as meteorologists use weather balloons to profile the sky, oceanographers use "CTDs" to plumb the depths. Named for what they measure, CTDs create a profile of water conductivity (which indicates salinity), temperature, and depth. For years, oceanographers have used large, towable devices like the winged workhorse SeaSoar, which was introduced in the 1980s to measure temperature and salinity.

The development of these instruments ushered in the modern era of front research 20 to 30 years ago. Each oceanographer has his or her own ideas about what technological advance has been the most important. Rudnick notes that for researchers at sea, "it was very difficult to know where you were other than very far from land" before GPS, which can tell a ship its location within 10 feet. Besides broad-use aids like satellite imagery and smaller, faster computers, a host of specialized devices have become indispensable.

Rudnick is developing a smaller version of





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the CTD for deployment as early as next year. This Underway CTD (UCTD) is a model rocket–sized version that promises to be vastly less expensive than current models.

With inexpensive devices, researchers can afford to have higher aspirations. Traditionally, oceanographers have towed their instruments behind research vessels or on willing "vessels of opportunity," usually cargo ships that navigate predictable tracks across the ocean. Rudnick hopes his 10-pound torpedo-shaped instrument will make a wider variety of boats eligible to volunteer services within the next few years. For instance, a yacht owner sailing from the U.S. West Coast to Hawaii could simply drop the UCTD behind the vessel and tow it. The yacht's owner could then download its data onto a laptop computer.

"The ocean is large and inhospitable, and we are able to measure only small bits at a time," Rudnick says. "A single ocean cruise usually is enough to convince a fresh graduate student of the difficulty of our field."

Also in development at Scripps is a self-propelled glider called Spray. The size and shape of a real torpedo with a bright-orange aluminum housing, Spray follows a preprogrammed route and measures temperature and salinity through a specified swath of ocean. It can be deployed from a small boat or ship and is able to operate autonomously for months on end, rising to the surface just long enough to transmit data to a passing satellite and receive new instructions.

It is one of several such autonomous devices being developed in oceanographic labs around the country. A recording network of thousands of such sensors could make estimating the ocean's mass easier, replacing the tenuous guesses scientists make now. In the oceans, often considered a frontier less explored than space, the answer to at least one mystery seems close at hand.

"The attraction of autonomous devices such as Spray and simple, widely distributed systems like UCTD is that we will be able to have measurements from more places at one time," Rudnick says. "Better observations will lead to better prediction of ocean weather."

And someday, better predictions of subsurface ocean weather are sure to lead us to better atmospheric forecasts over land as we learn more about how one affects the other. ☐