Coastal Upwelling: Physical Factors Feed Fish

Local winds, nearshore currents, and waves spawned by remote processes all influence the productivity of prime coastal fishing grounds

Seafaring fishermen seem to be born knowing where and when the fishing is good. Now oceanographers are starting to understand the physical, chemical, and biological processes that make some patches of sea much more productive than others. Prime fishing grounds are so fertile that they supply more than half of the fish harvest although they comprise less than 1 percent of the sea. What distinguishes these areas is that they are close to shore, and nutrients in the surface water are replenished frequently from deeper in the ocean.

Recent studies reveal that each superb fishing system responds to its own balance of remote and local physical influences. Local winds, coastline shape, underwater topography, and nearshore currents are among the factors that govern the rate at which nutrients are brought to the surface. An 8-year interdisciplinary study that concludes this year made the exciting discovery that winds hundreds of thousands of kilometers away can disturb the local currents and affect the fertility of a coastal fishing ground. The results of this study, the Coastal Upwelling Ecosystems Analysis (CUEA),* make it clear, says Richard Barber of Duke University, that "physical and biological processes are in a sequence, so understanding the ecosystem requires understanding the sequence. A [marine] biologist out there with no understanding of the meteorology or currents is just whistling in the dark."

According to Robert Smith of Oregon State University in Corvallis, CUEA data show that "the ocean's response to wind is usually very tight and very quick." Near Oregon, for example, where favorable winds blow intermittently during the spring and summer, the surface water close to shore receives "shots of nutrients followed by periods of relaxation," says Smith. The annual growth of large animals, such as sole, Dungeness crab, and salmon, is linked tightly with the total amount of favorable wind. According to Barber, before the CUEA study "the idea that the amount a crab grows is tied to the strength of the winds evoked hilarity."

Local winds bring nutrients to the surface by a process known as coastal upwelling, which was first fathomed by the Swedish oceanographer Vagn Ekman at the turn of the century. Ekman pointed out that wind acts together with the rotation of the earth to move the surface water. Prime upwelling areas are on west coasts, where prevailing winds blowing alongshore and toward the equator force the surface water to move away from shore. To fill the void left along the coast, deep water, rich in nutrients, moves shoreward and wells up to the surface. There phytoplankton consume the nutrients and fix the carbon needed to sustain the ocean food chain.

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While local winds are perhaps the most important factor controlling the onshore-offshore flow involved in upwelling, CUEA researchers find that a wind favorable to upwelling can be too strong for the ecosystem's good. Typically, the amount of nutrients brought to the surface and the growth of phytoplankton increase with the strength of the alongshore, equatorward wind. But this relationship holds only up to a point in the CUEA study area near Mauritania. If the wind blows harder, says Louis Codispoti of the University of Washington, more water is brought to the surface, but it is poorer in nutrients. Codispoti explains that nutrients upwelling in this area come from the undercurrent that flows toward the pole. "When the equatorward winds get too strong, they weaken the undercurrent, and the nutrient concentration declines."

Moreover, when the winds near northwest Africa are too strong, they mix the water too vigorously to favor optimum plankton growth, says Barber. The phytoplankton are stirred too deeply into the sea to benefit from the sun's rays. As if this deep mixing alone were not enough disadvantage, the turbulent water picks up sandy sediments from the bottom and the suspended particles reduce the depth to which light can penetrate.

Off the coast of Peru, however, some major fluctuations in the water flow are not at all coupled with variations in the local wind. These fluctuations are waves that travel southward along the Peruvian coast, but they are different from the visible swells on the surface of the sea. Fluctuations in the current associated with these subtle waves are observed sequentially on sensors along 700 kilometers of shoreline, according to Kenneth Brink of Oregon State. Although such "coastal-trapped" waves had been postulated theoretically, the CUEA team obtained the first firm evidence that they are real. Brink and Smith find that the waves travel about 200 kilometers in a day and have a wavelength of 1000 kilometers. Biological and physical oceanographers alike point to the discovery of the waves as one of the most exciting results of CUEA.

Energy carried by the waves may come from far up the coast or perhaps from the middle of the equatorial Pacific Ocean. Smith speculates that the waves, spawned by winds in the central Pacific, may propagate eastward along the equator and bump into the coast of South America. There they are trapped close to shore, with some of the energy carried northward and some carried southward toward Peru. Brink favors an alternative source for the waves, pointing out that some data suggest that the waves seen in

*CUEA is a $21.5-million program sponsored by the International Decade of Ocean Exploration of the National Science Foundation. It has involved researchers from 15 institutions, who have monitored currents, weather, water temperature, nutrient concentrations, and the plankton population continuously for several months at study sites near Oregon, Peru, and Mauritania in northwest Africa.

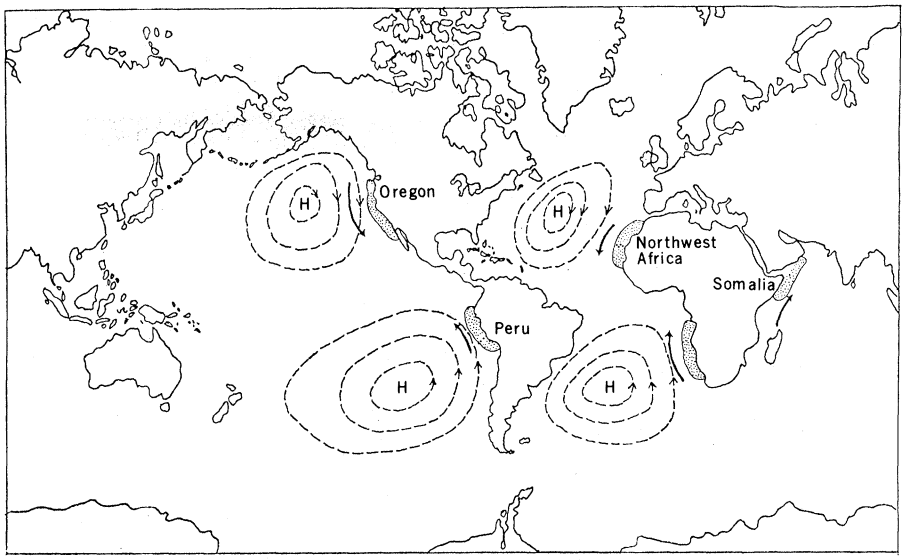
the study area may be whipped up by winds 10° farther north.

While coastal-trapped waves were discovered near Peru, new evidence hints that they exist near other shores as well. John Allen and David Enfield of Oregon State find them in the northern Pacific. There subtle variations in sea level seem to propagate northward past California, Oregon, and Washington. The waves weaken as they get farther from the equator.

Evidence for waves traveling along the Atlantic coast of the United States is not clear-cut, says Robert Beardsley of Woods Hole Oceanographic Institution. Although East Coast sea-level data have been viewed as clues to waves, many experts distrust the interpretation of those data. According to Leonard Pietrafesa of North Carolina State University in Raleigh, however, measurements of currents off the southeast coast of the United States indicate that there are waves there. But their signature is obscured because they are swept northward by the Gulf Stream faster than they propagate to the south—the direction they are supposed to travel, because they are on the western edge of an ocean.

Now oceanographers are debating whether or not El Niño—a sudden influx of warm water that devastates the Peruvian anchovy fishery every few years—is a wave. Many researchers hesitate to classify it as a wave because waves do not normally carry water large distances. Yet El Niño has some wavelike features. According to Dudley Chelton of Scripps Institution of Oceanography, El Niño affects the sea along the Pacific coast from Mexico to Alaska as well as near Peru. For instance, about 3 months after El Niño hits Peru, it seems to hit San Francisco. However, Chelton's analysis indicates that El Niño travels along the coast only one-fourth as fast as simplified theories predict—a fact that he cannot explain.

The Peruvian anchovy fishery has not yet recovered from the 1972 El Niño, and Codispoti suspects that the dearth of anchovies may have caused the changes he observes in the chemistry of Peruvian waters. Since 1976, fewer than 1 million tons of anchovies have been harvested per year (in good years more than 10 million tons have been caught). The chemical changes and adjustments in the food chain, which no longer has the anchovy as a major link, convince Richard Dugdale of the University of Southern California that the future of the fishery is bleak: "there appears to be no way to build the population up again." Barber is not so pessimistic; pointing to previous sudden rebounds in the population, he claims that the fishery may yet recover.



This map shows the major coastal upwelling regions of the world and the weather systems that drive them. Studies have been made of the stippled upwelling centers near Peru, northwest Africa, Somalia, and the western coast of the United States.

El Niño aside, Dugdale suspects that it is "probably not too unusual for coastal-trapped waves to have a major biological influence." It is this aspect of waves that has excited the biological oceanographers.

When the phytoplankton population changed drastically and suddenly in a study area near Cabo Nazca, Peru, measurements by the physical oceanographers indicated that a wave was to blame. The wave essentially flushed the study area of its denizens and imported new ones from the north. But since waves do not transport water, this occurred only because of the particular upwelling and current regime along the Peruvian coast.

Upwelling off Peru tends to be strongest in small patches. The patch at Cabo Nazca stays in the same place, but its size changes in response to the local wind. When the equatorward wind is stronger, upwelling is more vigorous and the patch is larger, reports John Van Leer of the University of Miami.

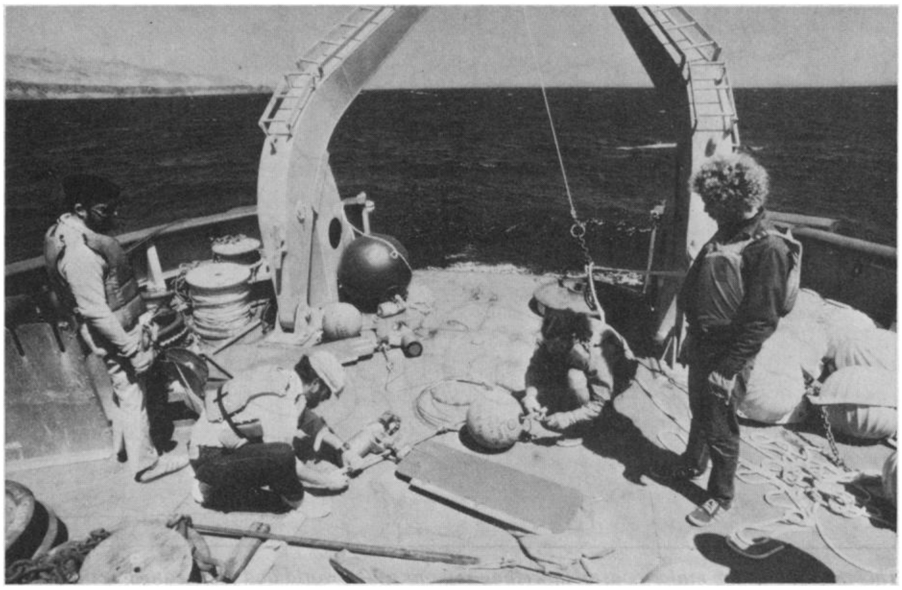
Normally, the slow, nearshore currents stabilize the biology of the upwelling center. As Van Leer puts it, "the system reseeds itself in part with nutrients and organisms" by the conveyor-like action of the alongshore currents and the upwelling. In Peru, as in the other CUEA study areas, the offshore-onshore upwelling circulation described by Ekman is superimposed on alongshore currents. On average, a surface current heads toward the equator, while an undercurrent heads toward the pole.

Upwelled water is carried out to sea and toward the equator by the combination of Ekman's wind-induced flow and the surface current. Phytoplankton thrive, as do zooplankton. Gradually some of the plankton sink into deeper water, where the undercurrent carries them poleward. Simultaneously the upwelling action moves them toward shore. Overall, many organisms may be welled into the same patch again.

The conveyor-like recycling was broken when the wave went by. All the water was moving poleward—the thin surface current was briefly erased. After the wave passed, the plume redeveloped its physical character rapidly, but the phytoplankton were slower to recover, as the "seed stock was transported out of the area and settled into water that was not coming back," explains Van Leer. The dominant species changed from diatoms to flagellates, and it took a month for the diatom population to build back up. Barber suspects that it took so long for the diatoms to recover because the wave changed the nutrient content of the upwelling water.

To James O'Brien of Florida State University, the stability, persistence, and rapid recovery of the upwelling center near Cabo Nazca are good clues that underwater topography may be another factor controlling upwelling. There is a small hummock on the continental shelf just south of the strong upwelling patch. In numerical models O'Brien finds that such a hummock deflects the undercurrent, and the resulting flow "looks like the upwelling center" in the study area.

Canadian oceanographers echo O'Bri-



Oceanographers on board the R.V. Alpha Helix *are preparing to put a string of instruments for measuring currents into the sea near Cabo Nazca, Peru (in the left background).* [*Source: Robert Smith, Oregon State University*]

en's belief that bottom topography can help bring nutrients to the surface steadily. Researchers at the Institute of Ocean Sciences near Victoria, British Columbia, find that the richest patches of sea near Vancouver Island† are just seaward and just shoreward of a shallow bank. Phytoplankton are very productive there and support a rich crop of salmon, herring, and bottom fish. But, says Kenneth Denman of the Institute, "the high level of surface nutrients does not appear to be directly associated with wind-driven upwelling." He speculates that the nutrients may be brought to the surface as the bank deflects the undercurrent or the flow coming out the nearby Straits of Juan de Fuca.

Submarine canyons and coastline geometry also appear to influence the strength of upwelling. Barbara Hickey of the University of Washington finds upwelling enhanced over canyons that cross the continental shelf of Oregon and Washington. Smith observes that upwelling is more intense on the equatorward side of capes than it is elsewhere.

Major ocean currents rather than winds seem to be the key agents nourishing rich ecosystems along the eastern edges of continents. "It was thought that the South Atlantic Bight [between Cape Canaveral, Florida, and Cape Hatteras, North Carolina] was a nutrient desert, without upwelling. But people were catching fish (menhaden) and now it appears that the Gulf Stream provides the nutrients," says Pietrafesa. Along with collaborators at the Skidaway Institute of Oceanography in Savannah and the University of Miami,‡ Pietrafesa finds that the southeastern U.S. coastal waters are nearly as rich in nutrients and plant life as many west coast upwelling areas are. Although local winds help bring nutrients to the surface, Pietrafesa believes that "the Gulf Stream is 90 percent responsible."

Meanderings of the Gulf Stream intrude some of its water onto the continental shelf, and this action forces nutrients to the surface. Periodically off the coast of the Carolinas, for instance, a sausage-shaped Gulf Stream meander herniates into coastal water. Warm water from the current feeds the sausage, and it elongates into a narrow filament paralleling the Gulf Stream. The resulting circulation wells cool, nutrient-rich water into the gap between the filament and the Gulf Stream. Pietrafesa finds that upwelling in another area (off Charleston) is triggered by the bottom topography, which deflects the Gulf Stream eastward.

In addition, Pietrafesa's studies reveal that large changes in air temperature can drive currents and induce nutrient mixing near shore. During winter, arctic cold fronts regularly travel as far south as the Carolinas. The polar air "can cool the whole water column by 6°C and induce currents within 2 days," according to Pietrafesa. Whereas cooling results in downwelling, rapid heating has the opposite effect and plays a major role in distributing nutrients during spring.

On the other side of the world, the ability of a strong current to drive upwelling is very dramatic. During summer, upwelling off the coast of Somalia is so intense that for 3 months of the year, phytoplankton fix carbon at a rate that rivals their productivity in Peruvian waters—one of the most fertile marine ecosystems in the world. Yet during the winter months, the region "looks like the Sargasso Sea—there is virtually nothing there," says Sharon Smith of Brookhaven National Laboratory. Although large marlin feast in the area, it is not commonly fished. Monsoon winds of 40 to 50 knots make for rough seas, and as Smith puts it, "the catch per unit of unpleasantness is much better elsewhere."

Summer monsoon winds in the Indian Ocean spawn the seasonal Somali Current that flows northward along the Somali coast. Where the swift current turns out to sea, the upwelling is extremely intense. According to Otis Brown of the University of Miami, water 7°C colder than normal is brought to the surface and swept 200 kilometers out to sea—much farther offshore than most upwelling systems extend. Although the cold water is full of nutrients, it is not entirely a blessing for the fish. Brown reports that they often die in large numbers, presumably from thermal shock.

Oceanographers were enticed to study the Somali area as part of the Global Weather Experiment,§ because satellite measurements showed striking variations in sea temperature in response to the monsoon winds. One and sometimes two large, cold upwelling patches were seen. During the cruise to the area last summer, there were two upwelling centers: the southern one was larger and forced almost entirely by the strong Somali Current as it turned out to sea; the northern one was smaller, driven in part by another current and in part by the monsoon winds. In most years there is upwelling only at the northern site, because the Somali Current usually hugs the coast and turns out to sea only when it reaches the northern center.

Taken together, the recent studies have fostered an improved understanding of the ways weather and currents control the biology in prime fishing grounds. While each upwelling system has its own quirks and responds to many influences, now "it is known that the systems follow rules which are knowable," says Barber.

—BEVERLY KARPLUS HARTLINE

†The Canadians are at the midpoint of the 2-year Coastal Oceanic Dynamics Experiment (CODE), a study of currents off the coast of Vancouver Island.

‡The Department of Energy has sponsored these ongoing studies of the circulation in the South Atlantic Bight since 1975.

§In 1979 the Indian Ocean Experiment (INDEX) probed currents and weather near the coast of Somalia and elsewhere in the western Indian Ocean.