The Ocean Above and the One Below

Earth has two global oceans. One is the thin film of water clinging to the rocky surface, the one with whales and seashells. The other is the ball of molten iron the size of Mars that forms Earth's fluid core. The flows within each are important to the surface's inhabitants, the flow of the core generating Earth's magnetic field and the flow of the water ocean playing a pivotal role in climate. Both oceans received considerable attention at December's American Geophysical Union meeting in San Francisco. Here are some samplings on each.

Is Our View of the Core Obscured by "Clouds"?

Geophysicists have thought of the magnetic field that sailors steer by as a kind of light that lets them see through 2900 kilometers of mantle rock to the fluid core, which generates the magnetic field. Follow the field back to the core, the reasoning went, map its shifting patterns over decades and centuries, and one should be able to decipher how millimeter-per-second currents within the core generate the magnetic field. But both theory and experimental results discussed at the recent American Geophysical Union meeting suggest that the view of the core may be distorted or obscured by a core-mantle boundary as messy as that between the water ocean and the air.

On the theoretical side, David Stevenson of the California Institute of Technology noted that the core-mantle boundary is a "wondrous place" where as many processes could be reshaping the boundary as operate on the rock at our feet. He outlined three possibilities. Molten core, which has the viscosity of water, could be sucked up into the mantle. The porosity required for significant infiltration could be formed within "inverted mountains" of mantle intruding the core. A column of slowly sinking mantle pushes the boundary a kilometer or more into the core, forming an inverted hill and applying the strain that could open porosity. Enough fluid might penetrate the mantle mountains to form a slush layer about 100 meters thick.

The core-mantle boundary could also be reshaped by the core's minor, mantle-like constituents freezing out at the prevailing temperature of several thousand degrees, depositing themselves at the boundary like morning frost on the ground. Earth has been cooling since its formation 4.5 billion years ago, noted Stevenson, which is long enough for 100 or 200 kilometers of rock to have deposited. That happens to be the thickness of a transition zone, called D″, which some researchers have compared to continents at the core-mantle boundary (*Science*, 1 August 1986, p. 523). Another process for change could be the core's eating away at the mantle. Where slow downwelling drives the mantle deeper into the core, the higher temperature and pressure that the inverted mountain is exposed to could drive chemical reactions that erode the mountain and redeposit core-rich material down stream in the adjacent inverted valley.

The boundary may be even messier than that. Raymond Jeanloz of the University of California at Berkeley and Elise Knittle and Quentin Williams of the University of California at Santa Cruz discussed their contention that mantle and core must inevitably react at the boundary. When they squeezed simulated lower mantle rock with iron foil in a laser-heated diamond anvil press, the combination reacted to form a mixture of metallic alloys, which would be highly conducting, and insulating oxides. A layer of such stuff, perhaps as thick as D″, would surely distort the view of core motions, the group contends, as its blobs of conducting alloy bend the field crossing the boundary much as bubbles in window glass would distort the view.

The latest such view was presented by Jeremy Bloxham of Harvard University and Andrew Jackson of Cambridge University. Actually it was one step short of core motions, being a movie of the shifting field lines at the core-mantle boundary as extrapolated downward from 300,000 observations made at the surface between 1820 and 1980. Their new analysis technique showed more clearly some features seen in an earlier map: an actively changing Atlantic hemisphere, a quiet Pacific hemisphere, and beneath southern Africa the formation of an upward-folded tube of magnetic field lines.

In the next talk, Jeffrey Love of Harvard and Bloxham argued that at least in the case of the southern Africa changes, they were seeing the effects of the core without misleading distortion by intervening mantle. Their explanation of that feature had been that upwelling core had picked up horizontal field lines normally confined to the core and pushed them out of the core to the surface. Jeanloz's reaction mixture at the boundary might be presumed to mask the effect of the core upwelling, but Love and Bloxham modeled the field above an upwelling core and, in the model, the field was still expelled from the core.

The broad area of unchanging core field under the Pacific is another matter, Bloxham noted. It could be an area of high iron content, as Jeanloz would have it, or the temperature of the lower mantle there could be anomalous, as suggested at the meeting by David Gubbins of Cambridge. Such a temperature variation in the lower mantle could entrain and stabilize the circulation of the core beneath it. It will be difficult to distinguish between these possibilities, said Bloxham, but probing with sufficient seismic waves is probably the way to do it.

The Big Picture of the Pacific's Undulations

As expected, last spring's switch in the tropical Pacific from the relatively warm waters of El Niño to the cold waters of La Niña has sent bone-chilling cold through Alaska and Canada this winter (*Science*, 26 August 1988, p. 1037). The sloshing of water about the Pacific that is intimately involved in such temperature switches is getting the most complete monitoring ever thanks to a convenient convergence of interests among civilian and military oceanographers.

The key to this new view of a major cog in the climate system is the U.S. Navy's GEOSAT satellite. It carries a downward-looking radar that 500,000 times a day measures the distance from the satellite to the surface, and thus the height of the surface, by timing the radar signal's round trip. The Navy, of course, had its own purposes in launching GEOSAT. The height of the sea surface responds to both deep-seated variations in the pull of gravity, which can send a ballistic missile off course, and the tug of unseen sea floor features such as seamounts, where antagonistic submarines might play their game of cat and mouse. Such sea level data were collected, and promptly classified, during GEOSAT's 18-month geodetic mission following its launch in April 1985.

Fortunately for civilian oceanographers, the National Aeronautics and Space Administration's SEASAT satellite had carried a slightly less precise radar altimeter. So when the Navy had finished its geodetic mission, it placed GEOSAT in an orbit that carried it exactly over SEASAT's tracks. Because the

SEASAT data were public property, so are the GEOSAT data from this exact repeat mission, which continues.

One use of the unclassified data has been the monitoring of rapid changes of sea level, as opposed to the sea surface's permanent distortions. Tide gauges on Pacific islands have been used for this before, but half of the Pacific has a dearth of islands. Laury Miller, Robert Cheney, and Bruce Douglas of NOAA in Rockville, Maryland, reported at the American Geophysical Union meeting that by taking the difference between the sea surface heights on consecutive passages of the satellite, they can measure month-to-month changes in sea level that reproduce tide gauge records within 4 centimeters.

The first thing the NOAA researchers noticed was an annual cycling of water between the equatorial Pacific (7°N to 7°S) and a band in the northern tropics (8°N to 20°N) that was driven by seasonal wind shifts. Starting late in the year, the sea surface would gradually drop about 10 centimeters in the equatorial band and rise 10 centimeters in the north. This shift of seawater would reverse before midyear. No water seemed to go to the south.

The annual cycle seen in 1985 repeated itself in 1986, but then in 1987 a 10,000-kilometer-wide, 20-centimeter-high wave of water, called a Kelvin wave, marched eastward across the Pacific following a burst of wind in the west. Thanks to the Kelvin wave, say Miller and Cheney, the equatorial band developed a 3.5-centimeter deficit with respect to earlier cycles, while the north tropical band developed a 5-centimeter surplus. The shift in behavior came early in 1987, near the peak of the 1986–87 El Niño, and the tropical band has maintained its deficit at least through the end of 1988, well into the cold La Niña. Throughout this episode, the amount of water between 20°N and 20°S remained unchanged. "We saw no real trends prior to El Niño," says Miller, "the equatorial area just emptied out. Whatever El Niño is, in terms of water level changes, it's entirely contained within 20° of the equator."

That suits Mark Cane of Lamont-Doherty Geological Observatory, one of a number of researchers running computer models of El Niño. He says that the timing and pattern of the water shift is just what would be expected in an ocean oscillation regulated by huge, slow-moving waves ricocheting east and west across the Pacific, as proposed for El Niño (*Science*, 11 December 1987, p. 1507). GEOSAT's failure to find a pre–El Niño buildup of water in the western Pacific, a long-discussed feature sometimes seen in the tide gauge records, reflects an oversimplification of how the Pacific is prepared for another warm episode, Cane says. The next step in the present cycle, he thinks, should be a slow trickle of water back to the Southern Hemisphere, returning the ocean to normal within the next year.

Eventually, GEOSAT sea level observations should become another type of input to El Niño models, improving both understanding and forecasting. But they have other uses for civilians. In addition to mapping sea floor topography and broad sea level anomalies, they can gauge wind speeds and wave heights. The pattern of small-scale sea level differences can even reveal currents like the Gulf Stream, eddies, and major boundaries between differing water masses. Those too are favorite features with which submarines can cloak themselves. It comes as no surprise then that the Navy is considering launching a second altimeter to double the frequency of observations. It too will be on an unclassified mission.

Did the Ocean Once Run Backward?

Despite those alluring ads for winter trips to the Caribbean, most ocean water is within a few degrees of freezing. The thin layer of surface water that in some places reaches balmy temperatures is an exception; the world ocean is filled nearly to the brim with icy water that got its chill while at the surface of polar seas.

But there is new evidence that the ocean depths of the geological past were not always so frigid. The global circulation that now runs from the poles to the deep sea to tropical surface waters may once have run in the opposite direction, with numerous implications for climate and life. At the American Geophysical Union meeting James Kennett and Lowell Stott of the University of California at Santa Barbara reported on their estimates of ancient seawater temperature made from two sediment cores retrieved by the drill ship JOIDES *Resolution* under the Ocean Drilling Program. The cores are from two sites on the Maud Rise off the coast of Antarctica having water depths of about 2000 meters and 3000 meters. Today water temperatures at those depths are about 2°C, the deeper site being about 0.5°C colder than the other.

This is the first pair of cores, says Kennett, that covers a range of water depths, records sedimentation over the period 20 to 60 million years ago, and is free of alteration that could affect paleotemperature determinations. For their analysis, Kennett and Stott used the oxygen isotope composition of microfossils of foraminifera that lived on the bottom. When the forams removed carbonate from bottom water to build their shells, the ratio of oxygen-18 to oxygen-16 depended on the temperature of the water, among other things.

The UC Santa Barbara group found that in the older part of the cores water at the deeper site was 2°C warmer, not 0.5°C colder, than at the shallower site. Both sites were then much warmer than today, about 13°C. About 45 million years ago, the ocean off Antarctica appears to have shifted to the present, coldest-on-the-bottom structure.

The simplest way to have turned the ocean upside down like that is to have run it backwards. Water flows to the deepest part of the ocean because it is the densest water around. But density depends on both temperature—colder is denser—and salinity—saltier is denser. Today most of the ocean's densest water is made in Antarctica's Weddell Sea, just west of the Maud Rise, where cold air and the exclusion of salt from freezing seawater combine to send surface water to the bottom of all the major oceans.

There is another, warmer way to make dense seawater. The climate of the Mediterranean is so warm that evaporation concentrates salt to the point that water spilling through the Strait of Gibraltar sinks to a depth of 1200 meters in the Atlantic, despite the escaping water's warmth. Most recently, it was Garrett Brass and John Southam of the University of Miami and William Peterson of Pennsylvania State University who suggested that 70 million years ago such evaporative densification might have won out over chilling in the competition to fill the deep sea. Earth was much warmer then, especially at high latitudes. And higher sea levels had flooded the continents, creating more warm, shallow seas where evaporation might predominate. If enough warm, highly saline water formed at low latitudes, it could have displaced any cold, saline water that may have been forming. The flow of deep waters would then have reversed, moving from low to high latitudes.

Brass and his colleagues point to two consequences of a reversed deep-ocean circulation. It may have caused the exceptional warmth in polar regions by altering the ways the ocean and atmosphere transport heat. And the lower solubility of oxygen in warm water could have led to anoxia of the deep sea and massive organic-rich deposits.

The reversed ocean, if it is confirmed, might in turn have resulted from the changing shape of Earth's crust. Sea level, for example, depends on how much water is displaced by mid-ocean ridges, which depends on the rate of sea floor spreading. Life's ties to the inanimate Earth can be subtle indeed. ■ RICHARD A. KERR