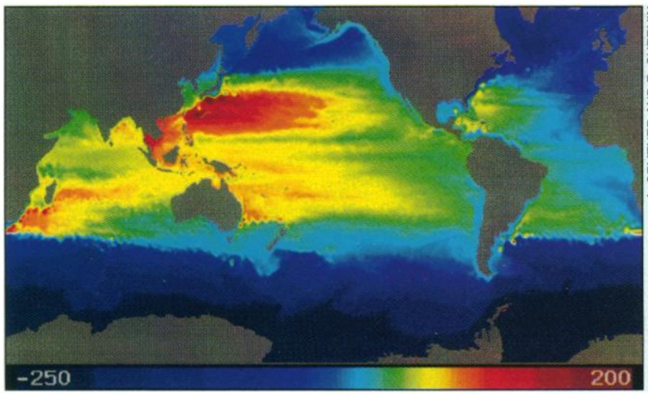
EARTH SCIENCE

Ocean-in-a-Machine Starts Looking Like the Real Thing

How do you get the billion-plus cubic kilometers of the world ocean into a box about the size of a telephone booth? Even when that box is a supercomputer and the "ocean" is actually a computer program that tries to simulate the ocean's behavior, oceanographers always have to leave out something vital. The real ocean is so complex that researchers have had to limit their modeling to just one part of it, or content themselves with a scale so coarse that key features of the ocean's circulation were lost. Now, by exploiting a parallel supercomputer, two modelers have managed to squeeze the entire world ocean into a box while preserving some crucial details such as the 50- to 100-kilometer-wide eddies that pinwheel around the ocean and the currents that snake through the narrow straits between ocean basins.

This best-ever simulation of the world ocean's behavior, developed by Albert Semtner of the Naval Postgraduate School in Monterey and Robert Chervin of the National Center for Atmospheric Research (NCAR) in Boulder, has been wowing other oceanographers. "I'm truly envious of what they've been able to do," says modeler Peter Killworth of Oxford University, who helps run the Fine Resolution Antarctic Model (FRAM) that covers the southern one-third of the world ocean (*Science*, 1 November 1991, p. 656). "It's important and exciting work," adds physical oceanographer Peter Rhines of the University of Washington. "You knew what was there, but when you see it all at once, it's stunning and you [also] see new things." Among them: a vast, looping current that connects the Pacific, Atlantic, and Indian Oceans. The current, postulated by oceanographers but difficult to map in its entirety in the real ocean, serves as a global "conveyor belt" of heat and salt and is thought to be a crucial link in the global climate machine.

The ability to create such features in a model bodes well for future efforts to simulate the entire climate system—the ocean, atmosphere, and polar ice sheets combined—in enough detail to predict climate change. And Semtner and Chervin's achievement is a proof-of-principle for climate modeling in another sense, too. Modeling the climate system will take hundreds of times more computing power than is available today, and parallel computers, built to carry out many simultaneous calculations, have been the great hope of climate modeling (see sidebar). Semtner and Chervin are the first ocean modelers to put some of that promise to the test.



A. SEMTNER AND R. CHERVIN

A model ocean. Differences in the height of the sea's surface trace flow across the Indian Ocean in a new global model.

The extra computer power enabled Semtner and Chervin to give their model something that had eluded modelers in the past: global coverage combined with a detailed view of ocean circulation. Computer models create that circulation by starting with a snapshot of the ocean, based on observations, then calculating how its circulation should evolve. At each time step, a model recomputes the position and properties of the water as it is stirred by winds and differences in density, which depend on temperature and saltiness. No conceivable computer could keep track of the temperature and motion of every molecule of water or salt in the ocean, so the models have to divide the ocean up into blocks and calculate their average properties. And just as the size of the tiny dabs of color in a pointillist painting is crucial to the overall effect, the smaller the blocks in a computer model, the more realistic its picture of the ocean.

As a benchmark of realism, oceanographers have singled out eddies. These small "storms" play an important role in ferrying heat and salt around the ocean. And eddies only emerge when a model simulates the ocean in blocks measuring roughly half a degree on a side or smaller. Semtner and Chervin's global model, as published last year, had only half-degree blocks, but they recently refined it to a quarter-degree on average and made other improvements. The result: When the model's output is rendered on video, eddies can be seen carrying heat across the great current that circles Antarctica, much the way atmospheric storms span the jet streams.

Semtner and Chervin aren't the first to reach eddy-resolving resolution. Both the FRAM model and the cooperative U.S./German Community Modeling Effort (CME) that is simulating the North Atlantic generate more or less realistic eddies by dividing the ocean into blocks about one-third of a degree square and some hundreds of meters thick. But because both of those models draw on more limited computing power, they can only capture part of the world ocean at such high resolution. Neither one can simulate how the ocean basins are interconnected into a single world ocean. "If you don't do a global model," says FRAM's Killworth, "you have to fake what happens at the edges" of your regional model. The FRAM model, for example, has a wall across the oceans near the latitude of South Africa. If water is to pass into or out of the walled-in Southern Ocean, as it does in nature, FRAM modelers have to decide how, when, and where. "If we get it right, it was because we said it was right," notes Killworth. "That isn't science."

The near-completeness of Semtner and Chervin's model—only the Arctic Ocean is walled out—is revealing things that simply can't show up in regional models. The centerpiece of Semtner and Chervin's early analyses is the looping "conveyor belt" flow. As oceanographers had pictured the flow, it carries warm, fresh surface waters from the Pacific through the Indian Ocean to the Atlantic, and up the Gulf Stream to the neighborhood of Iceland. By then evaporation has made the surface water saltier and thus denser; when the water gives up its heat to the cold north winds—in the process keeping Europe a good 6°C warmer than it would otherwise be—it becomes dense enough to sink into the abyss. The result is a return flow through the deep sea: a broad, slow flood carrying 100 times as much water as the Amazon that flows out of the Atlantic and back to the Pacific by way of the Antarctic Circumpolar Current.

Seeing the conveyor belt in action in Semtner and Chervin's global model is welcome support for physical oceanographer Arnold Gordon of Columbia University's Lamont-Doherty Earth Observatory, who had argued for its importance in 1986 based on skimpy observations. The model also supports him on some finer points as well. Observations still disagree about the relative importance of an alternative route for the conveyor that runs from the Pacific into the South Atlantic around the southern tip of South America rather than through the Indian Ocean. Gordon favors the route through the Indian Ocean, and so does the model,

The Parallel Route to an Ocean Model

Oceanographers Albert Semtner of the Naval Postgraduate School in Monterey and Robert Chervin of the National Center for Atmospheric Research (NCAR) in Boulder have done a better job of recreating the world ocean in a computer than any modelers before them (see main text). One element of their success is teamwork—in the form of a parallel supercomputer that solves many parts of the problem at once.

Their model is thus a first step toward harnessing for climate modeling the kind of power that parallel computers are expected to offer by the end of the decade. By then, massively parallel supercomputers could be crunching through trillions of calculations per second, hundreds of times faster than the fastest of today's machines. But capturing the power of parallelism won't be easy, as Semtner and Chervin's experience shows.

While conventional computers have a single processor that tackles a problem one step at a time, parallel computers put multiple processors to work on it. That strategy boosts the speed of computation, but figuring out how to divide up the problem to best advantage can be tricky. To tailor their ocean model to run on four-processor and eight-processor Cray supercomputers at NCAR, the two modelers "found out a lot more than we ever wanted to know about the hardware," says Chervin.

For a parallel computer to achieve its full potential, the problem has to be structured so that the processors can work independently much of the time, spending as little time as possible swapping data. But each property of the ocean—temperature, density, velocity—influences every other, so Semtner and Chervin had to look for some other way to split up their problem. Their solution was to assign each processor its own separate chunk of the ocean, so that communications among the processors could be minimized.

When Semtner and Chervin parceled out the ocean as best they could and optimized other aspects of the model, its speed on the four-processor Cray XMP jumped 15-fold from 30 megaflops to 450 megaflops. Moved to a Cray YMP with eight processors, the model sped up to gigaflop speeds. Even so, it would take 100 hours on the Cray YMP to simulate just 1 year of detailed ocean circulation—and a year is far too short to predict the ocean's behavior in a greenhouse world, which would play out over many decades.

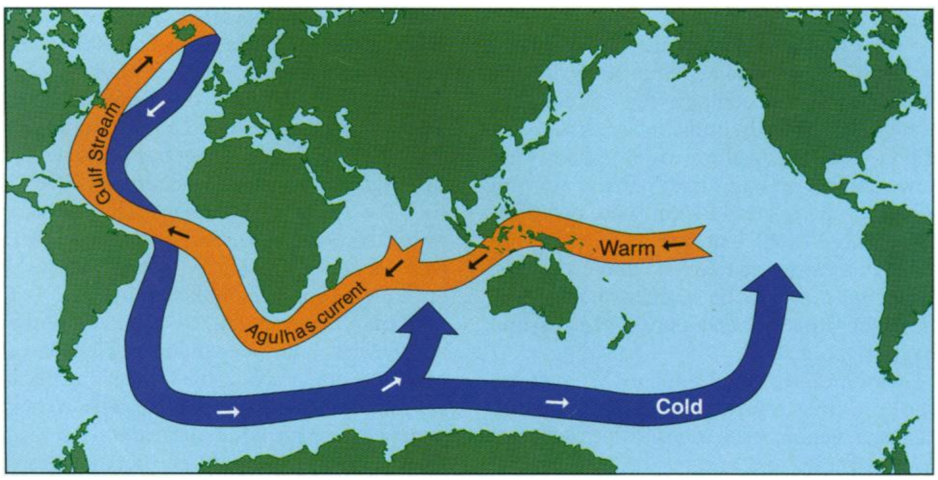
If ocean modelers are to contribute to climate prediction, they will have to move beyond machines with a dozen or so processors to massively parallel computers with thousands or even millions of processors. "You cannot think of simulating the ocean on anything but one of those," says modeler Dale Haidvogel of Rutgers University. As a start, Robert Malone, Richard Smith, and John Dukowicz of Los Alamos National Laboratory are running the Semtner and Chervin global model on a CM-5 Connection Machine with 1024 processor nodes. This CM-5's peak speed—on paper—is 128 gigaflops, but Malone isn't ready to say exactly how much of that speed he and his colleagues have been able to capture. But "the prospects are good for ocean modeling on massively parallel machines," he thinks. They better be. Anticipating the climate of the next century in any detail depends on it.

–R.A.K.

which has a hefty 17 million cubic meters per second passing into the Indian Ocean from the Pacific.

If the model is right about the dominance of the Indian Ocean route, it would have implications for the stability of the conveyor belt during climate change. In the model, explains Gordon, the Indian Ocean (a relatively salty ocean) is adding an extra shot of salt to the waters of the conveyor. That added salt could be crucial to the sinking of dense water in the North Atlantic under the present climate—and as a warming climate weakens the cooling there, the salt could help the conveyor resist a shutdown. That might spare Europe from a far more drastic climate shift.

But even Gordon is leery of taking the model's quantitative predictions at face value yet. "Of all the model results, I think you find Semtner and Chervin's look best," says Gordon, but he questions whether any model can accurately portray inter-ocean flows. And modelers themselves are quick to point out that there's a long way to go before their model oceans will resemble the real ocean enough to make forecasts about its behavior over the next century.



Around and around she goes. Driven largely by differences in water density, with help from the wind, a looping current brings warmth to Europe while storing greenhouse gases in the deep sea.

Other modelers, in fact, are eager to suggest improvements. William Holland of NCAR sees Semtner and Chervin's model as "marginally eddy resolving," especially at high latitudes; it will take a resolution of better than 1/6°, he says, to get all the eddies right. Rhines of the University of Washington wants better renditions of a number of physical processes that the model handles poorly or simply fakes. For example, although interesting details of the model's conveyor belt can be studied along most of its length, one turning point—where surface water sinks to form deep water in the North Atlantic—wouldn't be anywhere near right if it were left up to the model. For the sinking to continue, that part of the model ocean has to be reset periodically to match the properties of the real ocean.

But those shortcomings don't lessen some modelers' satisfaction at the progress represented by Semtner and Chervin's ocean-in-a-box. Says Dale Haidvogel of Rutgers University: "My feeling is that we're beginning to get to the point where global models are credibly realistic. . .that if they're doing something right, we can be fairly confident they're doing it for the right reasons." Killworth agrees. "We're now at an interesting time in ocean modeling," he says. "We've determined it can be done. Now it's a question of how it can be done best."

–Richard A. Kerr