Ocean Modeling: a Step toward Understanding the Earth's Climate

Matthew Hecht and Beth Wingate are working on two massive, interlocking problems with thousand-year time scales: ocean and climate modeling.

In a recent interview, Hecht, a staff member in CCS-2, the Continuum Dynamics Group in the Computer and Computational Sciences Division (CCS), said, "Much of ocean modeling is geared to climate (not weather)." He added, "Here, we also have specialized in shorter-term, very detailed simulation of ocean circulation."

Atmospheric modeling is complex, but ocean modeling presents a broader range of time and space scales. The oceans also store much of the available heat in the climate system. "There's just a lot more material in the ocean than in the atmosphere," Hecht commented. Going down just 10 meters below the sea surface doubles the pressure felt at the surface, because there is as much mass contained in 10 meters depth of water as in the entire column of air above. The ocean is essential to understanding climate not

only because of its role in the heat budget, but also because it holds much of the Earth's available carbon. The ocean's role as a source or sink of carbon dioxide to or from the atmosphere is determined primarily by water temperature.

The Rise of POP

In CCS, five staff members and two postdoctoral researchers are working on ocean simulation. Wingate, a staff member in CCS-2, said the cornerstone of ocean simulation is the Parallel Ocean Program (POP). She said it exists because of Bob Malone, a now-retired CCS-2 group leader. He saw an opportunity to take the best ocean model that existed at the time and make it work on massively parallel computers.

Malone is "a hero of nuclear winter," Wingate commented. He developed the "Nuclear Winter Prediction Model." He knew a lot about modeling of the atmosphere, she said—but he also had the insight to realize that if the work were done right, a smaller number of people could study ocean modeling successfully.

Hecht said ocean modeling doesn't require as many people because oceans do not have clouds—pesky structures that pose microscopic issues that constitute a very large problem in atmospheric modeling but cannot be ignored.

Wingate said the POP people in T-3, the Fluid Dynamics Group of the Theoretical Division (John Dukowicz and Rick Smith, at the time) "took the world's best model and made it run fast on parallel computers. Then, they started developing their own model."

Wingate added, "We also are working on new models."

Hecht does massively parallel, high-resolution calculations on the big machines at the Laboratory. He is also doing next-generation models. The products of his work are voluminous files of data, which can be analyzed to find out important things about ocean circulation or global warming. He also produces pictures that are a visualization of the data.

The North Atlantic Model

Wingate has a Ph.D. in atmospheric science and scientific computing from the University of Michigan. Hecht has a doctorate in theoretical particle physics "with a computational bent" from the University of Colorado-Boulder. He commented, "I didn't even think to study climate until I went to a seminar." A light bulb came on in his head that day, and he did his postdoctoral work in ocean modeling. Both of them have a background that includes work at the National Center for Atmospheric Research in Boulder.

Hecht was a postdoctoral researcher at the Laboratory between 1995 and 1997 when he worked with Rick Smith and Matt Maltrud in T-3 to develop a North Atlantic model. Hecht said, "It was a breakthrough simulation in terms of getting the most realistic picture anyone had seen of the Gulf Stream."

"You never really know if your model is sufficient until you do it," he commented. At the time, it was not known what resolution was required, nor whether the model physics was sufficient to achieve a realistic simulation of the Gulf Stream.

Wingate said that the effort for them to get a realistic picture of the Gulf Stream was as expensive in terms of memory as the entire coupled climate model. Hecht added that it was bigger than anything others were running at the time. He said they did it on the CM5 Connection Machine in the Advanced Computing Laboratory, headed at the time by Andy White, who had the necessary computing resources from the Department of Energy (DOE) Office of Science.

Recent Work

Hecht added, "More recently, we've been working to figure out how to model climate with an eddy resolving ocean." Maltrud, he said, is doing a global ocean-only simulation.

Wingate said their work involves a multidirectorate team with people from the Atmospheric, Climate, and Environmental Dynamics Group (EES-2) as well as T-3 and CCS-2.

Hecht added that their work is part of the Community Climate System Model. At one time, the ocean component was based on a National Oceanic and Atmospheric Administration model, not the Laboratory's DOE model (the POP code). Malone, Wingate said, was, "the captain who made everything possible on the ship."

The model is showing global warming. Hecht and Wingate said, "It's still a little bit of a judgment call" as to whether warming of this scale is man-caused or natural, but Hecht added, "It's a bit of a stretch (now) to see the warming of the last three decades as natural." They said that research on everything from tree rings to ice cores is indicating that the human race has created the problem. Hecht noted that the current retreat of ice is of particular concern. Because the ice is melting, he said, "The planet—like a black wall—is soaking up more sunlight."

Hecht's work on the Gulf Stream shows how relatively warm, salty waters feed into an area where dense waters are produced in the North Atlantic. Warm water flows to the north at the top of what has come to be called the Great Ocean Conveyor Belt. Cold water sinks to the bottom and flows south. "You're taking heat north," Hecht said. "The question is, how cold are those returning waters?"

It can take 1,000 years or more for water to complete a circuit of the conveyor belt.

Wingate is working on "overflows" in collaboration with the larger scientific community. She is looking at how dense water goes down the "slope" to the bottom, a process which, Hecht says, "we need to parameterize."

An Office of Science document, "Multiscale Mathematics Initiative: A Roadmap," published in December 2004, noted that breakdowns in this circulation pattern have in the past been associated with rapid climate changes.

The document said, "Similarly, the rapid warming we are currently experiencing could trigger an abrupt thermohaline shutdown and subsequent regional cooling. Numerical solutions have revealed that incorrectly predicting the 3d turbulence of the Kelvin-Helmholtz mixing can cause drifts after only 100 years of a 1000-year-long ocean simulation. In the Primitive Equations of motion that are used by most climate researchers worldwide, the small-scale phenomena are not included. If we continue with current models, then as computers get larger and as resolution increases, we will still not capture the phenomena described above. Instead, the processes are approximated by local empirical models that have to be changed with the changing resolution of each model run. Overflows could be resolved with a brute-force computational approach by resorting to the nonhydrostatic equations, but this would require a zeta-flop computer….

"The new challenge to applied mathematics and computing for global climate change is to formulate new equations, new models, and new numerical techniques that, when used in concert, self-consistently compute the feedback between the small scales and the climate scales."