> **“THIS WORK QUANTIFIES THE IMPORTANCE OF MODEL RESOLUTION TO SOLVE FOR THE DEEP-FLOW PATHWAYS OF THE ATLANTIC.”**

## BIGBEN & HYCOM

Since even before BigBen became a TeraGrid production resource in 2005, Garraffo — working with colleagues George Halliwell and Eric Chassignet and with PSC consultant John Urbanic and other PSC staff — has used this system to model the Atlantic Ocean. Her aim has been to validate and improve the performance of HYCOM (HYbrid Coordinate Ocean Model) — a distinctive model with a pedigree going back to the mid-1990s, when its forerunner, MICOM (Miami Isopycnic Coordinate Ocean Model), running on a Cray T3D at PSC, became the first model to correctly capture the "separation" of the Gulf Stream at Cape Hatteras, where it veers from a shoreline-hugging course northeast into the open sea.

The key to this breakthrough, as with the recent HYCOM modeling of the Nordic overflows, was sufficient computational capability to increase the grid resolution beyond what had before been possible. With the T3D, researchers could run the model on a massively parallel system and at a horizontal resolution of 1/12° latitude and longitude (equivalent to about six kilometers) for a decade of simulated ocean time. At lower resolutions, the coarseness of the model prevented it from accurately representing even such prominent features as the direction of flow past Cape Hatteras.

The problem is that improvements in resolution, such as from 1/3° (about 30 kilometers) to 1/12°, greatly increase the amount of computing required. Only with the availability of BigBen did it become feasible to use HYCOM to simulate the entire Atlantic Ocean for 40 years of ocean time even at moderate resolution. Garraffo's series of runs at 1/3° showed good agreement with historical observations and, further, test runs at 1/12° — using 1,936 BigBen processors — showed excellent agreement for sea-surface temperature, sea-surface height, and current transports.

The distinctive feature of HYCOM, inherited from MICOM and giving it a significant advantage in accuracy over other models, is that it is "isopycnic" — which means constant density. With this mathematically sophisticated approach, developed by University of Miami ocean scientist Rainer Bleck, the ocean is divided into vertical layers (HYCOM is typically used with 32 layers) so as to prevent spurious heat diffusion from depth to depth as the model progresses in time, with each layer preserving its own water mass.

HYCOM builds on MICOM by extending its usefulness to shallow coastal areas, where it allows finer vertical resolution to capture the turbulence of near-shoreline effects. The advantages of HYCOM led to its being chosen as the next-generation ocean model by the U.S. Naval Oceanographic Office and by the National Oceanic and Atmospheric National Centers for Environmental Prediction.

## NORDIC OVERFLOWS

In 2008, Garraffo began collaborating with Özgökmen, Chang and Peters to address the Nordic overflows. Is it possible, they asked, to realistically model the deep pathways of these overflows and, if so, what horizontal resolution is required?

Garraffo and Chang used computers at the University of Miami to run HYCOM for the North Atlantic, including part of the Norwegian Sea, first at 1° resolution (about 100 kilometers) then at 1/3°. For the high resolution run at 1/12°, Garraffo turned to BigBen at PSC.

The model seafloor was crucial. Prior to actually initiating the simulation of flows, the model used interpolation routines to represent seafloor topography from "bathymetric" maps of the underwater channels and ridges. The researchers found that for low resolutions the standard interpolation routines seriously distorted these features. "At low resolution," says Garraffo, "the model can't see all the channels because they are under resolved."

One of the main overflow passages is a narrow, deep channel north of the Faroe Islands, the Faroe Bank Channel (FBC). While the 1/12° model essentially captured the FBC topography, the 1/3° model underrepresented its depth by 200 meters, and at 1° the FBC vanished from the model.

Chang, Peters, Özgökmen, and Garraffo carefully examined all the available deep-flow observations for comparison with the modeling. They found that the three simulations showed clear and strong resolution-dependent differences, and the differences increased — as the models ran for 19 months of ocean time. At 1° the overflow can't find its path through the FBC, and the cold water masses go the wrong direction. Although the overflow pathways at 1/3° are more realistic, the model results still disagree with observations, with most of the overflow water ending up in the wrong ocean basin. "The 1/12° resolution," says Garraffo, "is not excellent, but at least it allows you to see the current and eddies."

"We find that the mean structure of the overflows in Denmark Strait and Faroe Bank Channel are simulated only at the highest resolution," says Özgökmen. "Severe problems with the lower resolution cases extend far beyond the actual overflows to large parts of the deep circulation."

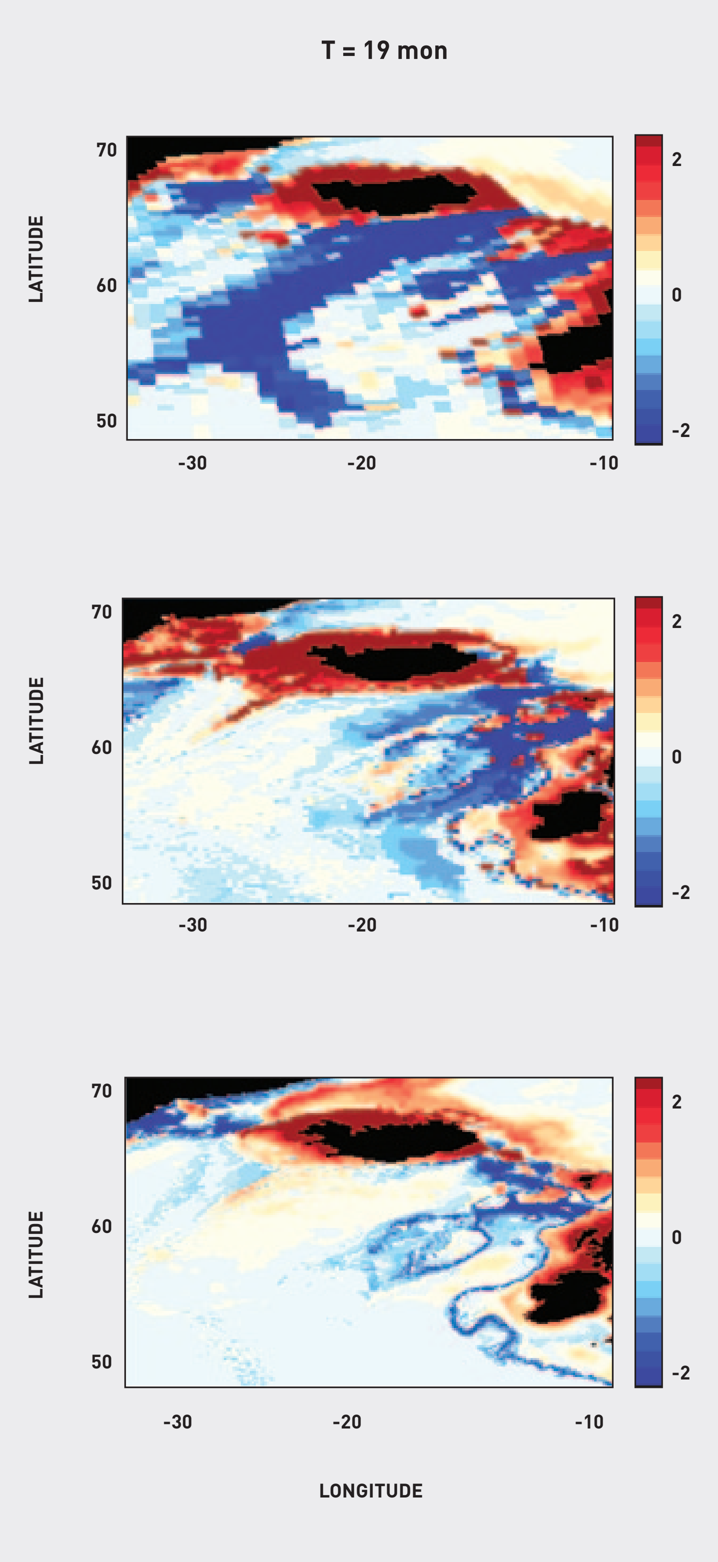
In an experiment to see if they could improve the results for deep circulation resulting from topographic errors, the researchers manually corrected the topography in several ridges and channels for 1° resolution. This simulation reduced errors in some areas, but increased discrepancies in other parts of the overflow region. Manual correction to bathymetry could have some limited usefulness, the researchers conclude, and they suggest that standard topography-generating algorithms be used carefully with coarse grids.

Their main conclusion, nevertheless, is that higher resolution, hence more powerful computing, is needed for climate modeling. "These results," the researchers say in their paper, "demonstrate the importance of an accurate representation of the domain geometry, in particular the channels of the complex Iceland-Scotland ridge system, in order to reproduce the pathways of the deep AMOC."

"Climate or ocean models," says Özgökmen, "run at 1° can't resolve these channels and canyons. They don't get the deep water right, and so they cannot describe correctly the deep pathways and transports. To produce fairly realistic overflow and AMOC, the resolution needs to be an order of magnitude larger."

**MORE INFORMATION**

www.psc.edu/science/2009/deepwater/



SEA-SURFACE TEMPERATURE CONTOURS

Temperature differences of the ocean surface indicate flow patterns of the cold overflows out of the Nordic Seas into the North Atlantic. These three views show results at three different resolutions (low to high) after 19 months of simulated overflows. At 1°(top) most of the cold water masses, rather than passing through the Faroe Bank Channel (FBC), are pushed south over the wider Iceland-Faroe Ridge. At 1/3° (middle) only a small part of the overflow turns toward the northwest to pass the partially blocked FBC. At 1/12° (lower) there are no unrealistically strong currents, and the overflow, as it should be, is concentrated in the FBC.