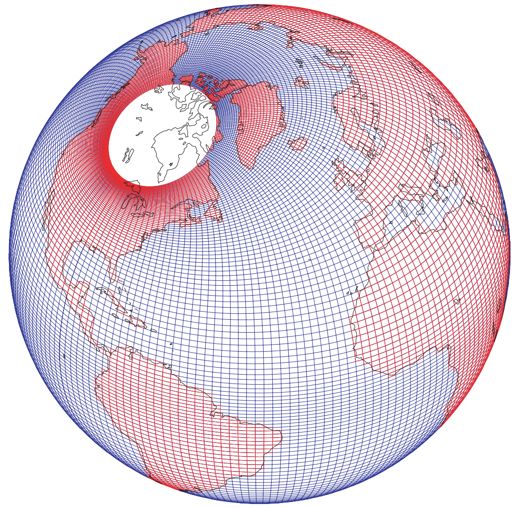
Eddy-Resolving Ocean Modeling



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Weather forecasting has been developed into a fine art, with elaborate data collection systems feeding present conditions into detailed computer models. Despite this great effort, it appears to be impossible to predict weather for more than about two weeks in advance. Yet we hope to predict the effects of greenhouse gas emissions and other human-induced effects on climate decades to centuries into the future. This goal may, in fact, be possible because what we call climate is really the statistical "envelope" of weather events, and thus we are asking for much less detailed information than would be necessary to forecast weather.

Earth's climate is controlled by the complex interaction of many physical systems, including the atmosphere, the ocean, the land surface, the biosphere, and in the polar regions, sea ice. To be able to predict future climate change, or at least to determine what can and cannot be predicted, we have to understand both the natural variability of the climate system and the extent to which human activities affect it. The ocean is of key importance in understanding climate, because changes in ocean circulation patterns are believed to be of primary importance in controlling climate variability on time scales of decades to centuries.

Unfortunately, realistic global ocean simulations pose a severe computational problem because the ocean contains both very small spatial scales and very long time scales compared with the atmosphere. Most of the kinetic energy in the ocean is contained in the so-called "mesoscale eddies," whose sizes range from 10 to 300 kilometers. These eddies constitute the "weather" of the ocean. They are the oceanic equivalent of high- and low-pressure systems in the atmosphere, where the spatial scales are much larger. Weather fronts typically extend over distances of 1000 to 3000 kilometers.

Whereas the spatial scales are smaller, the time scales in the ocean are much longer than in the atmosphere. Temperature anomalies in the atmosphere persist for at most a few months (unless they are associated with longer-term anomalies in the ocean surface temperature, as occur in an El Niño event). The ocean, because of its inertia and large heat capacity, has a much longer memory. Water mass properties in the deep ocean can reflect conditions that existed at the surface hundreds of years in the past. Residence times of deep-water masses are typically several hundred years and more than a thousand years in the deep Pacific Ocean. Because of this phenomenon, the integration time required to "spin up" an ocean model from an initial state of rest to a near-equilibrium state is several thousand simulated years.

Using the computer resources available today, it is not possible to integrate a basin- or global-scale ocean model with a resolution of about 10 kilometers (or about 0.1° resolution in longitude) for 1000 years or more in a reasonable amount of time. On the machines available in the United States, the global 0.1° simulations discussed below typically require about one week of computer time per simulated year, so a 1000-year simulation would take nearly 20 years to execute. On the Japanese Earth Simulator, currently the world's fastest supercomputer, the same model runs more than 10 times faster. But we still need another factor of 50-to-100 increase in computing power before multicentury, eddy-resolving climate simulations become feasible, and it will likely be at least a decade before such resources become available.

Another major issue is data storage. Typical model output from a 0.1° global model is about 1 terabyte per simulation year, so archiving, analysis, and long-term data storage pose severe problems. Because of these limitations, ocean models that are now being used in multicentury global climate simulations have spatial resolutions ranging between 1° and 4° (or about 100 to 400 kilometers), whereas models with resolutions of 0.1° (or about 10 kilometers) can run simulations of decades only.

During the past 12 years, Los Alamos has built the Climate, Ocean, and Sea-Ice Modeling (COSIM) project, with support from the Department of Energy (DOE). Our emphasis has been on the development and application of ocean and sea-ice models, but research is shifting toward fully coupled global climate modeling. In collaboration with the National Center for Atmospheric Research (NCAR), we are developing coupled climate models using low- to moderate-resolution ocean components. The NCAR community climate system model, which is the most widely used, fully coupled climate model in the United States, uses the Parallel Ocean Program (POP) model and the sea-ice model CICE, both developed at Los Alamos. These models were designed to run efficiently on parallel computer architectures and employ novel numerical algorithms that improve both the numerical efficiency and physical accuracy of the simulations. Los Alamos is also the home of the isopycnal ocean model HYCOM, which uses density instead of depth as the vertical coordinate (except in the surface mixed layer). More information on climate, ocean, and sea-ice modeling at Los Alamos is available on our web server: http://www.acl.lanl.gov/climate.

A major emphasis of our research over the last decade has been to make use of the supercomputing resources at Los Alamos for very high resolution, eddy-resolving ocean simulations, albeit of relatively short duration, using the POP model. This approach is the main focus of this article. Ten to 20 simulation years is sufficient time for the model to reach a quasi-equilibrium state, where the velocity field has adjusted to the initial density field. These short simulations are therefore appropriate for studying the dynamics of the ocean circulation on time scales of a decade or less, but they are not appropriate for studying the long-term evolution of deep-water masses or climate variability on time scales of decades and longer.

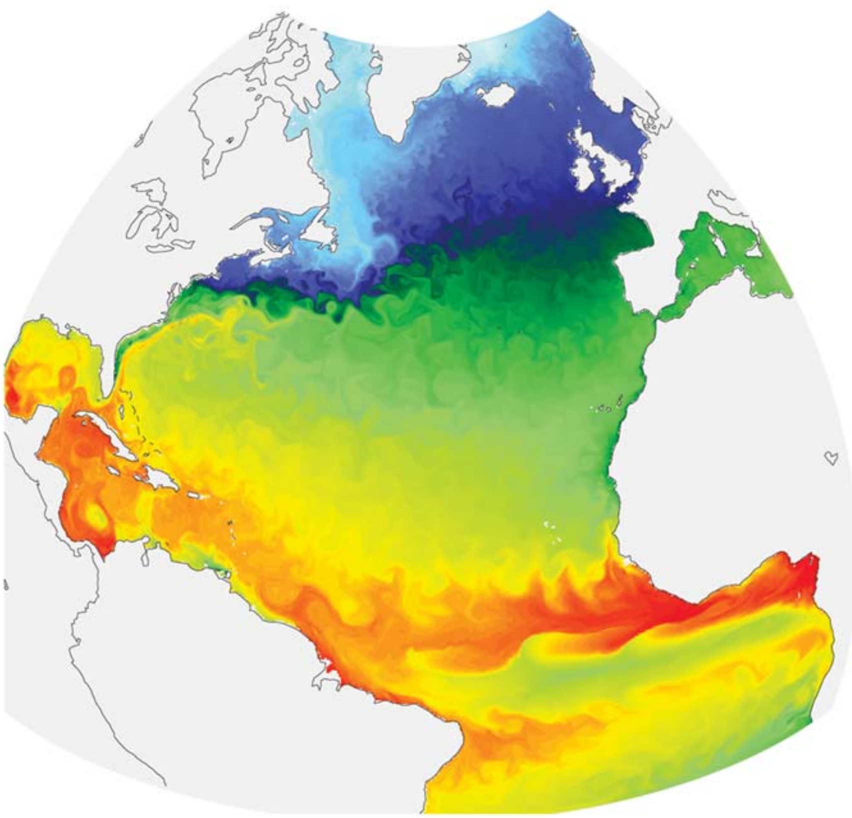
Nevertheless, the high-resolution simulations are very important for climate research since the model output provides realistic fields of turbulent statistics (such as eddy fluxes of mass and heat) that can be used to guide the development of subgrid-scale (SGS) parameterizations for use in coarse-resolution climate simulations. Understanding the behavior of these models will also pave the way for future eddy-resolving climate simulations. Furthermore, the model provides comprehensive three-dimensional datasets that can aid in the interpretation of the extensive observations taken over the last decade, such as high-quality satellite altimetry measurements and the variety of in situ measurements collected as part of the World Ocean Circulation Experiment (WOCE).

What Drives the Ocean Circulation?

The ocean circulation is driven by fluxes of momentum, heat, and fresh water at the air-sea interface. Fluxes of momentum are due to stress from the surface winds and from the movement of sea ice in polar regions. The surface wind stress is the primary driver of the upper-ocean circulation and is responsible for the major current systems, such as the midlatitude gyres with their associated strong western boundary currents (that is, the Gulf Stream off the east coast of North America and the Kuroshio Current in the Pacific off the east coast of Japan). Surface wind stress also drives the complex system of equatorial currents in the tropics, as well as the Antarctic Circumpolar Current in the Southern Ocean.

The other drivers of circulation—fluxes of heat and fresh water—are collectively known as buoyancy fluxes because they produce changes in the density of seawater, which depends on its temperature, salinity, and pressure. The surface heat flux is caused by incoming solar radiation, outgoing long-wave radiation, latent heat associated with evaporative cooling, and direct thermal transfer, also known as "sensible heat flux," which is due to differences in air and sea-surface temperatures. Fluxes of fresh water are primarily associated with precipitation and evaporation in the open ocean but are also due to melting or freezing of sea ice in polar regions and river runoff in coastal regions. The heat flux modifies the density of seawater by altering its temperature, whereas the fresh-water flux modifies the density by changing the salinity of seawater.

The buoyancy fluxes are the primary drivers of a circulation known as the thermohaline circulation, which is characterized by very localized sinking of dense water in subpolar regions and broad upwelling at low and mid latitudes. The thermohaline circulation is a very important factor in the earth's climate, because it controls the transport of heat by the ocean from the tropics to high latitudes, as well as the rate of formation of deep water in subpolar regions.



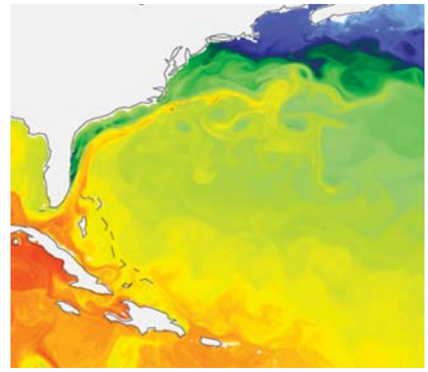


Figure 1. Ocean Heat Transport
In Earth's climate system, the ocean and the atmosphere each contribute about half the total transport of heat from the tropics to high latitudes. The figure is a snapshot of sea-surface temperature from a 0.1° simulation of the North Atlantic Ocean. Red colors indicate warm water, and blue colors, cold water. The Gulf Stream, which follows the coastline of the southeastern United States, carries warm water from the tropics to high latitudes. (Inset) This magnified view focuses on the Gulf Stream. In this simulation, it correctly separates from the coast at Cape Hatteras.

The North Atlantic Ocean at 0.1° Resolution

Our first major simulation performed with the POP model was a global ocean simulation driven by observed surface winds for the decade 1985 to 1995 (Maltrud et al. 1998). (The ocean circulation is driven primarily by surface winds, but surface fluxes of heat and fresh water are also important. See the box on the opposite page.) This model had a horizontal resolution of 0.28°, corresponding to a grid spacing ranging from about 30 kilometers at the equator to about 10 kilometers at high latitudes. (The variation in grid spacing occurs because this model uses a Mercator grid, in which the grid resolution in both the north-south and east-west directions varies as the cosine of latitude. The grid spacing is shown as a function of latitude in Figure A on the next page). The 0.28° resolution was sufficient to allow the development of a weak eddy field, but the eddy energy was much too low compared with observations. Although it was able to reproduce many aspects of the wind-driven circulation, this simulation, like other "eddy-permitting" simulations conducted by different researchers, was unable to reproduce basic features of the mean circulation, such as the points at which western boundary currents (for example, the Gulf Stream) separate from the coastlines or the observed paths of major current systems such as the North Atlantic Current, which flows northeast along the Grand Banks east of Newfoundland. Such errors can lead to huge mismatches between modeled and observed air-sea heat fluxes and can lead to incorrect feedback in coupled models.

The reasons for the deficiencies in this and other eddy-permitting simulations are still not completely understood, but detailed analysis of the global simulation compared with satellite observations (Fu and Smith 1996) clearly demonstrated the need for even higher spatial resolution, and theoretical arguments suggested a horizontal resolution of 0.1° or higher would be needed to capture the bulk of the energy in the turbulent mesoscale eddy field. At that time (1997), a global simulation was not feasible at this resolution, so we opted to conduct a limited-domain simulation of the North Atlantic Ocean at 0.1°, using a grid containing about 50 million ocean grid points. This model, also driven by observed winds, covers the period 1985 through 2000 (Smith et al. 2000). The model domain extends from 20S in the South Atlantic to 72N, and includes the Gulf of Mexico and the western half of the Mediterranean Sea.

Figure 1 shows a snapshot of the

sea-surface temperature from a 0.1° North Atlantic simulation. The path of the Gulf Stream, which carries warm water from the tropics to high latitudes, can be clearly seen. The current follows the coastline of the southeastern United States until it separates from the coast at Cape Hatteras; from that point on, it begins to meander and pinch off warm and cold core eddies. In lower-resolution simulations, the Gulf Stream does not separate at Cape Hatteras as observed. This discrepancy has been a long-standing problem with ocean circulation models.

Eddy Variability. A remarkable feature of the 0.1° simulation is the emergence of a ubiquitous mesoscale eddy field that is substantially stronger than had been seen in previous simulations and which is, by many measures, in good agreement with observations. The eddy kinetic energy constitutes about 70 percent of the total basin-averaged kinetic energy in the North Atlantic. The model results agree well with observations of the magnitude and geographical distribution of near-surface eddy kinetic energy and sea-surface-height (SSH) variability. (Regions of strong SSH variability correspond to regions of strong, highly variable currents and turbulent flow. See the box on this page.). The model results also agree with the wave number versus frequency spectrum of surface height variations in the Gulf Stream, as well as with measurements of the eddy kinetic energy as a function of depth in the more quiescent eastern basin. The model appears to be simulating realistic values of kinetic energy over a broad range of space and time scales.

Figure 2 shows the root-mean-square (rms) SSH variability from the model, averaged over a 4-year period, as well as a recent high-quality blend of altimeter data from the TOPEX/Poseidon satellite and the satellites

Currents, Sea-Surface Height, and Satellite Altimetry

The leading-order balance of forces in both the atmosphere and the ocean is between the Coriolis force, which is due to the earth's rotation, and horizontal pressure gradients. This state is known as geostrophic balance. The Coriolis force is proportional to the earth's rotational frequency and to the magnitude of the local current velocity, but it is directed perpendicular to the velocity (to the right in the Northern Hemisphere).

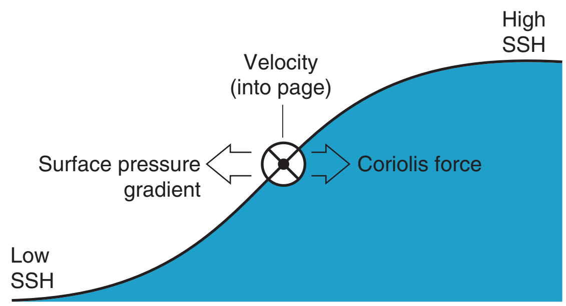


Figure A. Geostrophically Balanced Near-Surface Current
The pressure at a given depth is, to leading order, given by the weight of the overlying water column, which varies with the SSH. A drop in the SSH produces a horizontal pressure gradient that is balanced by the Coriolis force, which is proportional to the current velocity.

In the ocean, the Coriolis force associated with a near-surface current is in geostrophic balance with the horizontal pressure gradient because of changes in sea-surface height (SSH), as shown in the figure in this box. Thus, the near-surface pressure gradients are proportional to gradients of SSH. As a result, contours of constant SSH approximate streamlines of the near-surface flow, just as, in the atmosphere, contours of constant pressure (isobars) approximate streamlines of the winds.

In principle, an accurate map of the SSH would allow us to determine the near-surface currents. In practice, absolute measurements of SSH are difficult because the location of the sea surface in the absence of any flow is poorly known. If the ocean were at rest, the sea surface would coincide with a gravitational equipotential surface known as the geoid. Existing measurements of the geoid are not accurate enough to allow precise measurements of absolute surface height. However deviations of the SSH from the geoid can be made with much greater accuracy. Typical vertical fluctuations in the SSH associated with strong currents and eddies are about 1 to 3 meters, whereas modern satellite altimeters can measure vertical changes in SSH relative to the geoid with an accuracy of about 1 to 2 centimeters. Thus, the noise in the measurements is an order of magnitude smaller than the signal, and this situation allows very accurate measurements of the SSH variability, such as those shown in Figures 2 and 4.

sent by the European Remote-Sensing Satellite (ERS) Programme (Le Traon and Ogor 1998, Le Traon et al. 1998). This type of satellite data has revolutionized our understanding of the world ocean, because it provides a time series of surface properties with near-global coverage (instead of, for example, a snapshot of a limited section of the ocean resulting from a series of instrument casts obtained along a research vessel cruise track). The level of agreement between model and observations evident in Figure 2 is unprecedented. It represents a milestone for both numerical ocean modeling and satellite altimetry. In fact, time series of two-dimensional fields of surface height from the model are now being used by scientists in the United States and in France to help interpret the existing satellite altimetry measurements and to aid in the development of the next generation of satellite altimeter experiments.

Time-Mean Circulation. Although the agreement between the model and observations in eddy variability is impressive, what is most remarkable about the 0.1° simulation is that the time-averaged, or time-mean, circulation exhibits several significant improvements relative to previous simulations. Figure 3 shows the time-mean SSH from the model. As discussed in the box on the opposite page, contours of constant SSH approximate streamlines of the near-surface flow, and strong currents are associated with sharp drops in SSH across these contours (that is, in stronger currents, the streamlines are "crowded together"). Major current systems such as the Gulf Stream and the North Atlantic Current are clearly visible in the figure. The Gulf Stream separates at Cape Hatteras, and its peak velocities, transports, spatial scales, and the cross-stream structure of the current are in good agreement with current-meter data. South of the

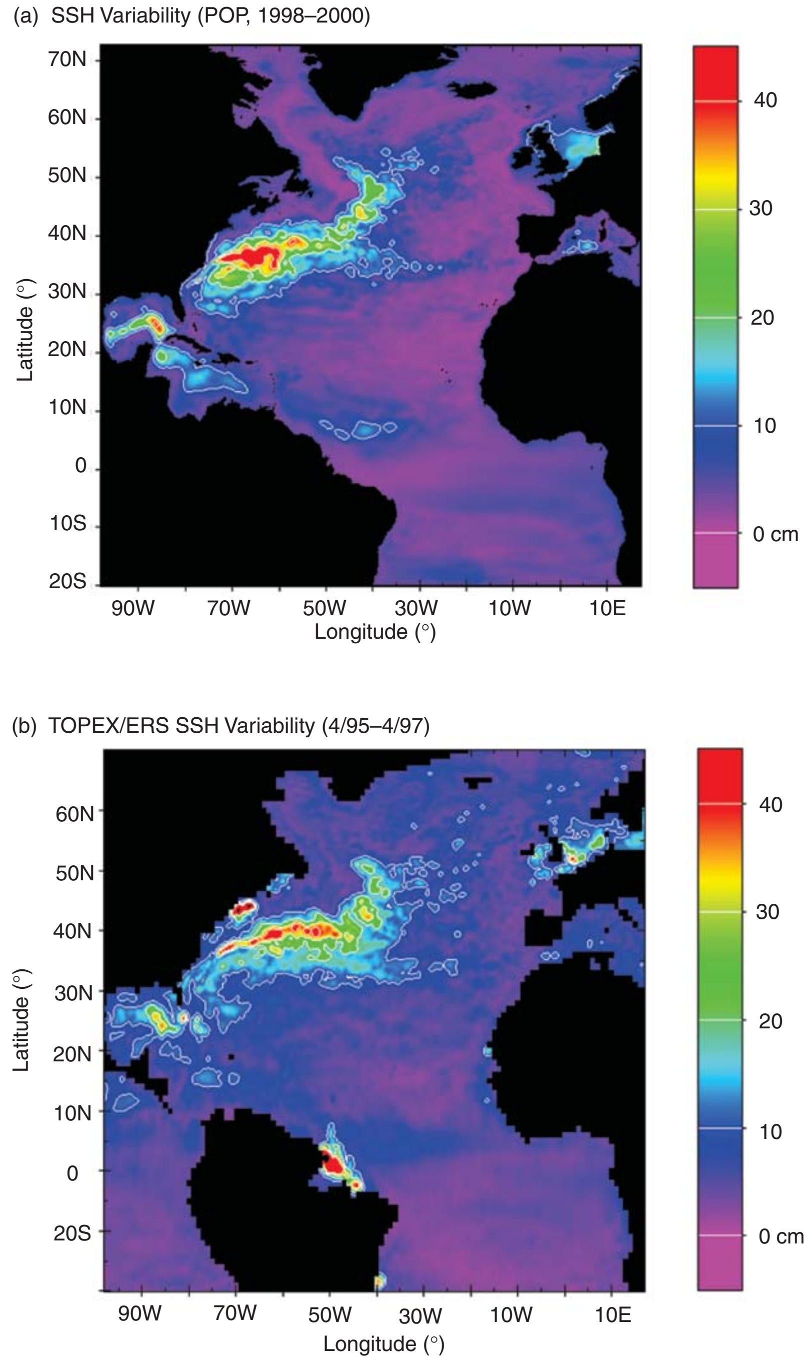


Figure 2. SSH Variability in the North Atlantic Ocean
Panel (a) shows the 0.1° POP model simulation of SSH variability, whereas (b) shows altimeter observations derived from data from the TOPEX/Poseidon, ERS-1, and ERS-2 satellites. The SSH variability is related to mesoscale turbulence, which is generated by instabilities of the mean flow, and hence the eddy field is most intense in regions of strong western boundary currents. The height variability is most intense in the region of the Gulf Stream extension (around 30N to 45N latitude and 75W to 50W longitude) and in the vicinity of the North Atlantic Current (40N to 50N and 50W to 35W). Some regions of high variability that appear in the observations but not in the model (such as off the west coast of South America near the equator and off the North American coast southwest of Nova Scotia) are residual errors associated with the removal of tides from the altimetry measurements.

Grand Banks, the Gulf Stream splits into the northeast-flowing North Atlantic Current and a southward flow that feeds the Azores Current. The time-mean path of the North Atlantic Current is in good agreement with observations from float data, including the detailed positions of troughs and meanders. This is the first realistic simulation that correctly simulates the Azores Current, which flows eastward at about 35N in the central and eastern basin. Its position, total transport, and eddy variability are consistent with observational estimates. (The surface height variability for this current can be seen in Figure 2 as a tongue of high variability between 30N to 35N and 40W to 20W that appears in both model and observations.)

This simulation is by no means perfect; there are notable discrepancies with observations in some areas. For example, the Gulf Stream separates at Cape Hatteras, but its eastward path after separation is about 1.5° too far south. Nevertheless, the overall improvement in the time-mean flow relative to previous simulations indicates that we have crossed a threshold in resolution and entered a new regime of the flow that is much closer to the real circulation of the North Atlantic.

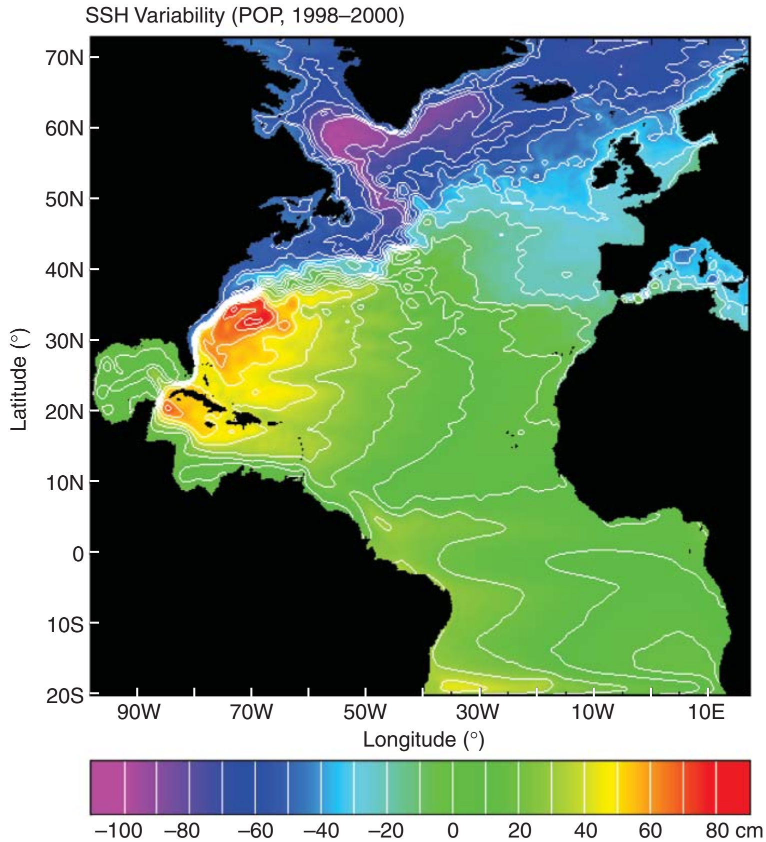


Figure 3. Mean SSH in the North Atlantic Ocean
Mean SSH from a 0.1° POP model simulation. Contours of constant SSH approximate streamlines of the near-surface flow. Sharp drops in SSH across these streamlines indicate the presence of strong geostrophic currents.

What is responsible for this regime shift? We do not yet know the complete answer to this question. It is likely that the increased resolution alone is responsible for much of the improvement. The resolution is high enough that we are able to resolve the typical length scale of the eddies (the Rossby radius) and hence capture the bulk of the energy in the eddy spectrum. (See the box on the opposite page.) The improvements in the mean circulation strongly suggest that the turbulent eddy field plays a crucial role in determining the character of the mean flow. Another contributing factor is undoubtedly the improvement in the representation of the bottom topography. Unlike atmospheric circulation, ocean circulation is very strongly constrained by the bottom and coastal boundaries, and using the latest high-resolution data sets for ocean depth, we are much better able to represent the coastal and sea-floor topography in this high-resolution model. Another feature that changes dramatically at high resolution is that currents like the Gulf Stream become much stronger, narrower, and deeper than in the lower-resolution simulations. These deep currents in many areas reach the ocean floor (in agreement with observations) and are therefore much more strongly influenced and steered by the bottom topography. In contrast, in coarse- and moderate-resolution models, currents like the Gulf Stream are unrealistically broad and shallow, and are not as strongly influenced by the bottom topography.

It should be emphasized that going to 0.1° or higher resolution is not in itself a guarantee that the simulation will show the same improvements we have seen. Several other modeling groups have now begun to carry out very high resolution simulations, and not all of these have had the same success. An example is the global 0.1° model discussed in the next section. Although simulations with this model do show improvements in many areas, they have so far been unable to reproduce the correct path of the North Atlantic Current, which,

Geostrophic Turbulence: The Weather of the Ocean

Weather maps at midlatitudes show wavelike horizontal excursions of temperature and pressure contours superposed on eastward mean flows such as the jet stream. These disturbances can "pinch off" and evolve into large-scale eddies that encompass the familiar high- and low-pressure centers. Similar excursions of the mean flow are found in the ocean in eastward-flowing currents such as the Gulf Stream. These disturbances are due to an inherent instability of the midlatitude jets known as "baroclinic instability," which occurs in the presence of strong horizontal density gradients. It is believed that baroclinic instability is the dominant mechanism for generating turbulent motion in the midlatitude jets. (Another type of instability, known as "barotropic instability," can also generate large-scale turbulent flow in the atmosphere and ocean. This instability occurs in the presence of strong horizontal shear and is more dominant in the tropics.)

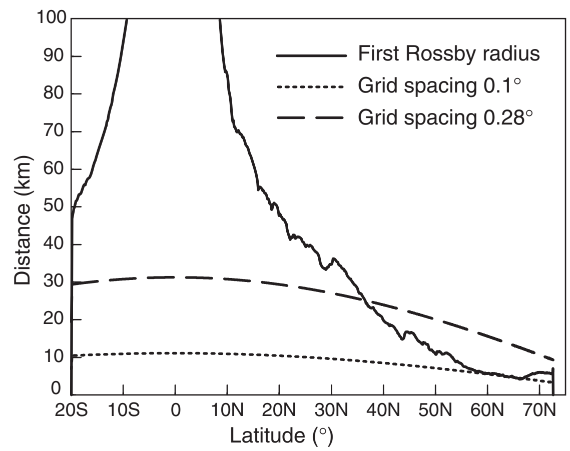


Figure A. Zonally Averaged Rossby Radius
The zonally averaged Rossby radius is computed from the time-mean density of the 0.1° North Atlantic POP simulation. This radius is compared with the grid spacing of the 0.1° and 0.28° POP models.

Baroclinic instability occurs in rotating, stratified fluids, with strong geostrophically balanced currents, which are associated with steeply sloping density surfaces. Turbulent energy is extracted from the potential energy of the mean flow that is stored in the sloping density surfaces of geostrophic currents. The net effect of pinching off an eddy from an eastward jet is to flatten the slope of the density surface, thus releasing potential energy. This instability is very different from the more familiar shear-flow instabilities such as the Kelvin-Helmholtz instability, in which perturbations grow by extracting energy from the mean shear flow.

A key feature of baroclinically unstable flow, which distinguishes it from most other types of turbulence, is that it has an inherent length scale, known as the "deformation radius" or "Rossby radius." This radius is the horizontal length scale associated with unstable modes having the largest growth rate. Perturbations with wavelengths much smaller than the Rossby radius do not grow, whereas those with wavelengths much larger than the Rossby radius grow very slowly. The Rossby radius depends on the degree of stratification (or vertical density gradient) and on the local vertical component of planetary rotation. The figure shows the Rossby radius in the ocean as a function of latitude averaged over the east-west direction, computed by using a mean density field from the 0.1° North Atlantic simulation. Also shown is the horizontal grid resolution in the 0.28° and 0.1° models discussed in the text. A key feature of the 0.1° simulation is that the grid resolution is less than or equal to the Rossby radius at all latitudes. Typical mesoscale eddies have horizontal diameters that are three to 10 times larger than the Rossby radius, so the 0.1° grid is expected to allow at least marginally good resolution of the eddies at all latitudes. This fact is undoubtedly a key reason that this simulation shows substantial improvements in eddy variability.

instead of turning northeast at the Grand Banks, continues eastward across the Atlantic, as it does in lower-resolution models. This error leads to large mismatches between the modeled and observed surface heat fluxes. We are in the process of investigating the reasons for this difference in the global and North Atlantic models.

Sensitivity Experiments. One thing we have discovered is that the solutions are very sensitive to the choice of SGS parameterizations of horizontal viscosity and diffusion. Initially, we had hoped that, at this

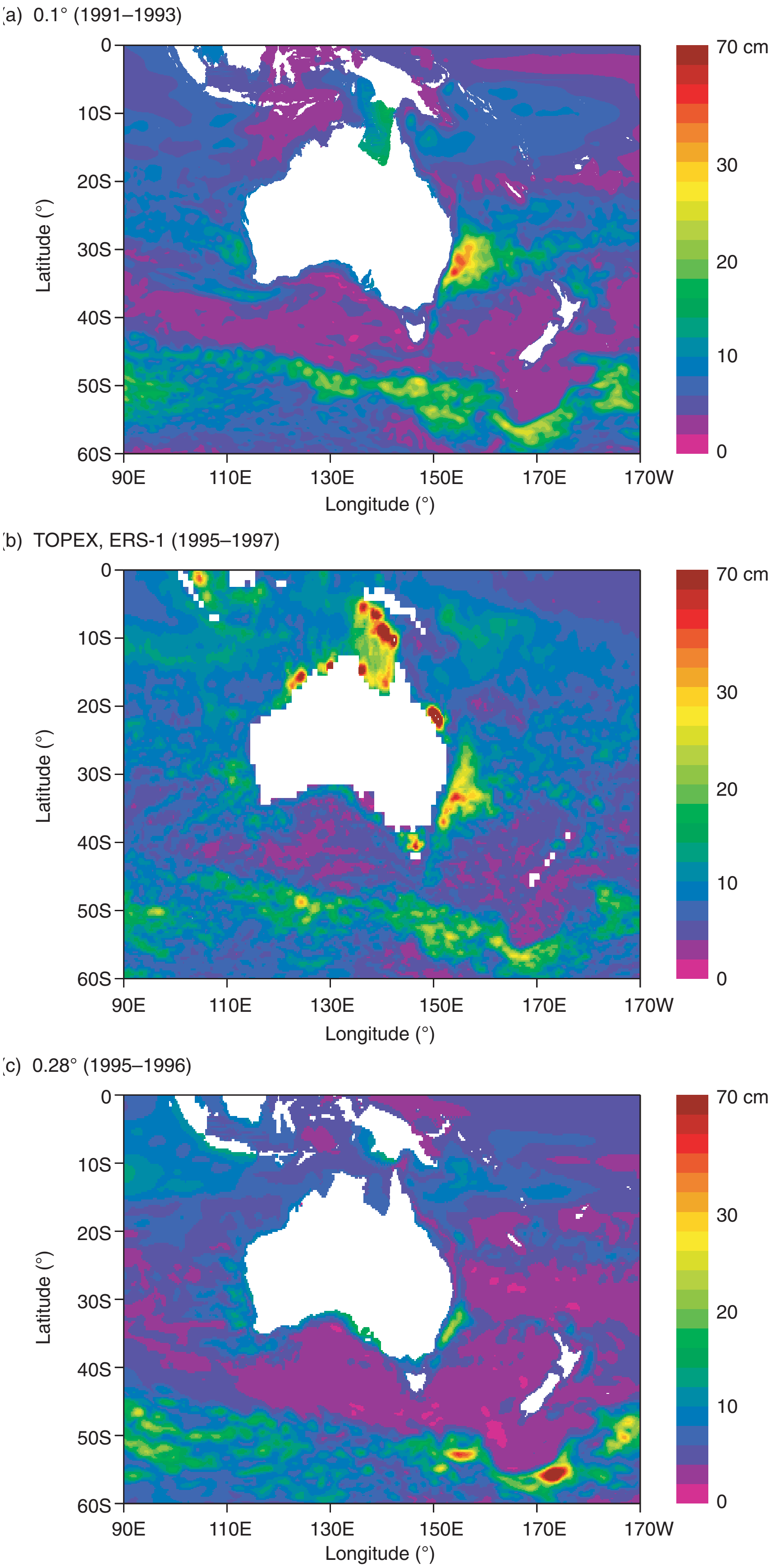


Figure 4. SSH Variability in a 0.1° Global Simulation

The rms SSH variability in the Southern Ocean near Australia is (a) from the global 0.1° POP model, (b) from the blended analysis of data from the TOPEX/Poseidon, ERS-1, and ERS-2 satellites, and (c) from the global 0.28° POP simulation. The agreement with observations is much better in the 0.1° model, especially in regions of strong currents such as the East Australia Current (near 30S, 155E) and the Antarctic Circumpolar Current (across the domain between 45S and 60S). The localized regions of high variability along the northern coast of Australia and south of New Guinea in the observations are residual tidal errors.

high resolution, we would simply be able to pick the coefficients of viscosity and diffusivity to be as small as possible to control numerical noise that appears on the grid scale, but that was not the case. Using the smallest possible mixing coefficients leads to unrealistic features, and the best solutions are obtained with larger values. This fact suggests that even at 0.1° resolution, we need to parameterize the effects of unresolved physical processes. We are investigating the sensitivity of the solution to different values of the mixing coefficients—as well as to different formulations of the SGS parameterizations—with a suite of new 0.1° North Atlantic simulations. We have developed novel SGS parameterizations that use horizontally anisotropic forms for viscosity and diffusivity, and we have shown that these lead to improvements in the solutions compared with the more standard isotropic forms. What we learn from these sensitivity studies in the North Atlantic model is being transferred to the more expensive global 0.1° simulations.

Global Simulations

Spurred by the success of the 0.1° North Atlantic simulations, we have configured a 0.1° global ocean model. It uses a "displaced-pole" grid developed at Los Alamos (Smith et al. 1995), similar to the one shown in the opening graphic. Standard grids that use lines of constant latitude and longitude as coordinates have a singularity that is due to the convergence of meridians at the North Pole. The displaced-pole grid eliminates this singularity by displacing the northern grid pole into the North American continent. This grid includes the entire global ocean except for ocean points within the circle surrounding Hudson Bay. This model, containing more than 300 million grid points, is expensive to run. Both the Department of Defense (Navy) and the DOE provided computational resources that allowed the completion of a 15-year simulation. More recently, several 15-year simulations have been run on the Japanese Earth Simulator. Figure 4 shows the rms SSH variability in a section of the Southern Ocean surrounding Australia from both the 0.1° and 0.28° global models and satellite observations. As in the North Atlantic simulation (Figure 2), the agreement with observations is much better in the 0.1° model.

The immense computational resources required to run these simulations make sensitivity experiments extremely difficult, not only because of the amount of computer time involved but also because of the severe problem of archiving and analyzing the immense amount of data produced by each run. Each simulation must be carefully planned and designed. The next generation of supercomputers will make this task more tractable and allow us to move closer to the goal of a fully coupled, global climate model with an eddy-resolving ocean component. The experience we are gaining today in our basin- and global-scale ocean simulations will pave the way for these future climate models. ■

Acknowledgments

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For more information on POP, CICE, and climate modeling at Los Alamos, including references and documentation for these models, see http://www.acl.lanl.gov/climate.

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