

TOM KLEINDINST

Mike Spall runs an ocean circulation model.

Wave-Induced Abyssal Recirculations

Turning This Way and That Way

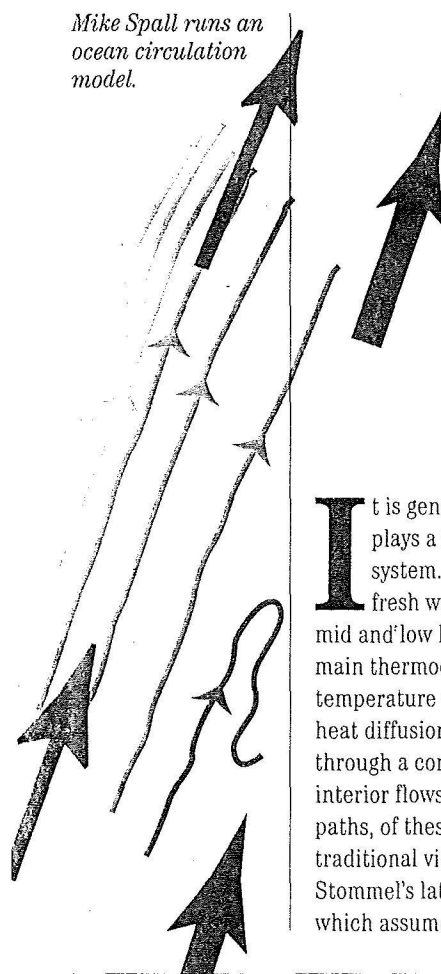
Michael A. Spall

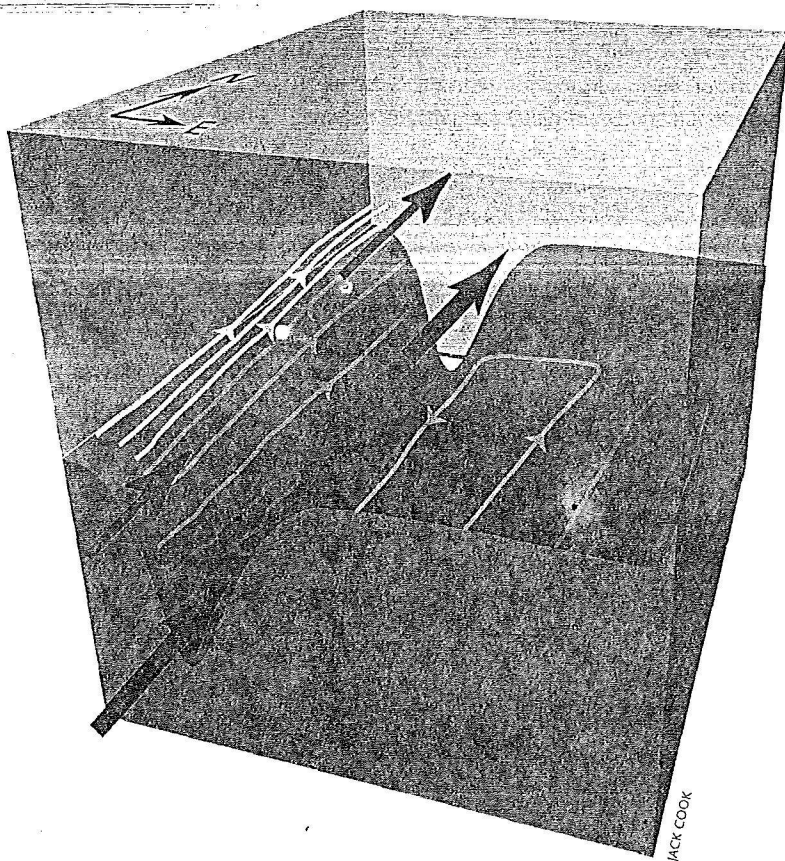
Associate Scientist, Physical Oceanography Department

It is generally believed that deep-ocean circulation plays a fundamental role in the global climate system. The abyssal circulation transports cold, fresh water formed at high latitudes toward the mid and low latitudes, where it upwells to maintain the main thermocline (a region of rapid decrease in temperature with depth) in the presence of downward heat diffusion. This is thought to be accomplished through a complex pattern of boundary currents and interior flows, although the dynamics, and even the paths, of these flows are not well understood. The traditional view of abyssal circulation stems from Henry Stommel's late 1950s and early 1960s theoretical work, which assumes that deep waters are formed in very

small regions at high latitudes and uniformly upwell throughout the lower latitudes into the upper ocean. This simple model predicted that a series of deep western boundary currents in the world's ocean basins would carry the waters away from their regions of formation, and that the basin interiors would be characterized by very weak poleward flow.

However, recent basin-scale hydrographic measurements in the North Atlantic and in the Brazil Basin of the South Atlantic Ocean (the location of the World Ocean Circulation Deep Basin Experiment) indicate that strong flows are not confined to the western boundary regions. Instead, the abyssal ocean appears to contain significant large-scale recirculation gyres,





Schematic of the mean circulation of Antarctic bottom Water from the model with an unsteady deep western boundary current. The deep western boundary current still flows to the north along the western boundary, but now the direction of flow in the basin interior is anticyclonic (counter-clockwise) with a raised center. The unsteady western boundary current entirely changes the mean-flow direction in the basin interior.

recirculation gyre in the basin interior. The flow indicated here is essentially void of any time-dependent motion.

To investigate the influence of time-dependent motion, we repeat the calculation above with reduced bottom drag, which allows small perturbations in the mean flow to grow into large amplitude waves and eddies. The schematic above indicates that the mean deep western boundary current continues to flow to the north, but now the mean interior circulation is anticyclonic (counterclockwise), opposite to that found in the absence of time-dependent motions.

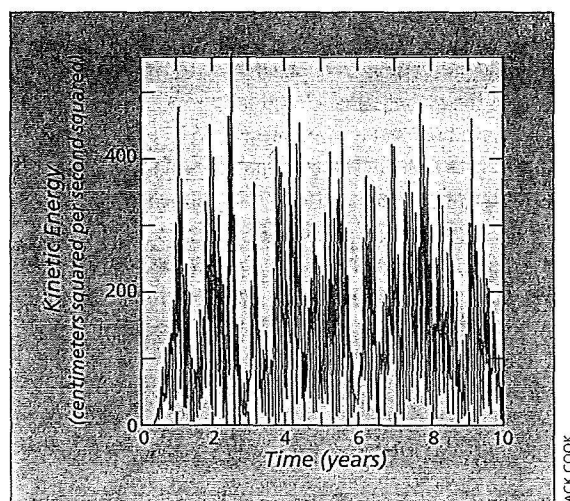
The nature of the variability near the western boundary is indicated in the figure at right by a kinetic-energy time series over the sloping bottom near the boundary. We find the passage of high-frequency events with velocities as fast as 15 to 20 centimeters per second about once each year. These currents are much faster than the mean speed of the deep western boundary current, which is approximately 3 to 4 centimeters per second. These energetic events are the signature of topographic Rossby waves that are generated by meandering of the deep western boundary current and that propagate downslope into the deep basin interior. These waves carry energy from the deep western boundary current into the basin interior and entirely change the direction of flow around the deep basin.

Recent observations of Antarctic Bottom Water circulation within the Brazil Basin indicate the presence of a basin-scale anticyclonic recirculation gyre with strength and distribution similar to that found in the model when waves are allowed to develop. Other

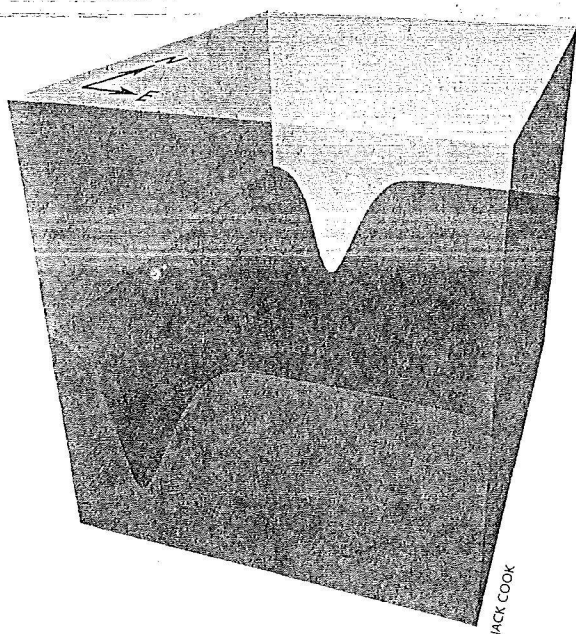
aspects of the observations agree with the model circulation, including an eastward flow of lower and westward flow of upper Antarctic Bottom Water. A key to determining if the observed large-scale recirculation gyre is a result of wave propagation over the western slope, as predicted by the model, would be the presence of topographic waves with energy propagation into the basin interior. RAFOS floats and current meters recently deployed as part of the World Ocean Circulation Deep Basin Experiment should be helpful in testing this hypothesis. (See Nelson Hogg's article on page 22 for a discussion of the float experiment.)

This work is supported by the National Science Foundation and the German Bundesminister für Forschung und Technologie. The main part of the research described here was carried out while Michael Spall was visiting the Institut für Meereskunde in Kiel, Germany. A manuscript describing this work has been submitted for publication in the Journal of Marine Research.

Michael Spall became interested in oceanography while working on his Ph.D. in Applied Mathematics at Harvard University. He came to Woods Hole in 1990 after spending a postdoc at the National Center for Atmospheric Research in Boulder, Colorado. He enjoys spending time with his family, sailing, fishing, playing volleyball, and studying oceanography.



Kinetic energy over the sloping bottom near the western boundary. The high-frequency variability marks the passage of topographic waves that are generated in packets by the meandering deep western boundary current about once per year. Energy these waves carry into the basin interior causes the large scale recirculation gyres seen in the two previous figures to change directions.



Schematic of the model domain representative of the Brazil Basin in the South Atlantic Ocean. The basin is bounded to the west by South America, to the east by the Mid-Atlantic Ridge, to the south by the Rio Grande Rise, and to the north by the Ceara Rise. Narrow channels allow Antarctic Bottom Water to flow into the basin from the south and out to the north, where it crosses the equator and enters the North Atlantic Ocean.

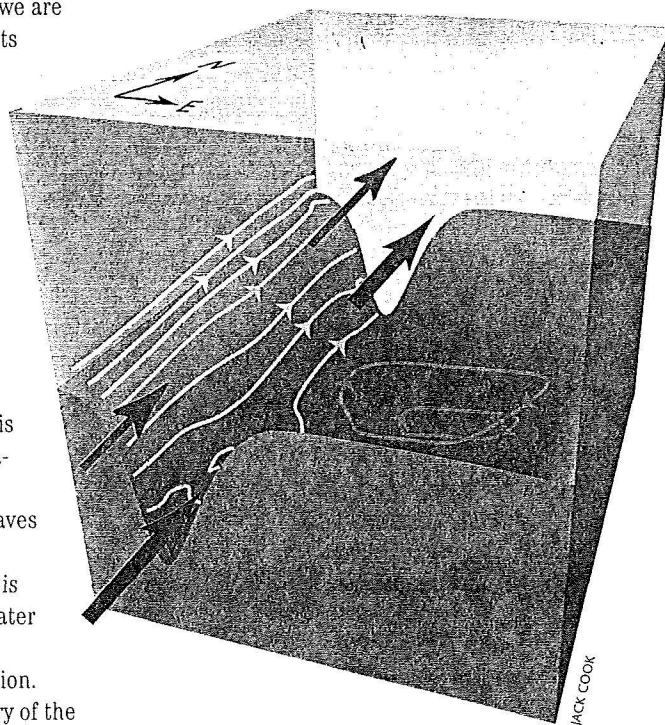
cross-basin flows, eastern boundary currents, and topographic waves (see Mike McCartney's article on page 5 for a discussion of the deep mean flows). The presence of these currents implies that the deep ocean is influenced by more complex physics than were included in the simple early models. Understanding the structure and forcing mechanisms of abyssal recirculation gyres, and their relation to the deep western boundary currents and upwelling, is essential if we are to fully understand deep-ocean circulation and its role in the global climate system.

I have been using a numerical model to investigate some of the consequences of more complex physics on abyssal circulations. The model approximates the continuously stratified ocean as three constant-density layers. The two deeper layers represent the lower and upper Antarctic Bottom Water (Antarctic Bottom Water is a cold, fresh water mass that originates near Antarctica and flows into the Brazil Basin from the south); the shallowest layer represents the upper ocean. This system is well suited for studying abyssal circulation because it allows for steep and tall bottom topography, time-dependent motions, such as waves and eddies, and vertical mixing between water masses. The effect of mixing between the layers is parameterized here as a uniform upwelling of water between the deeper two layers.

The figure above shows the model configuration. The domain is roughly patterned on the geometry of the

Brazil Basin, with bottom topography approximating the deep bowl shape of the Brazil Basin between the South American coast and the Mid-Atlantic Ridge. The basin's southern and northern limits are partially blocked by ridges, representing the Rio Grande Rise in the south and the Ceara Rise to the north. The basin extends approximately 3,000 kilometers in the north-south direction and 2,000 kilometers east-west. We know that Antarctic Bottom Water is formed at very high latitudes in the southern oceans and spreads northward, passing through the Brazil Basin into the North Atlantic. We approximate this flow into the Brazil Basin by introducing a deep western boundary current of Antarctic Bottom Water through a channel at the southern boundary of the domain. The flow exits through a channel adjacent to the western boundary at the domain's northern limit. Transport within each outflow layer may be different from that at the inflow, allowing for overall warming of bottom waters.

We have conducted two sets of experiments, one with a steady and one with an unsteady deep western boundary current. We keep the physical configuration—stratification, topography, and flow strength—constant, and render the flow steady by increasing the current's drag against the bottom. This approach allows us to investigate the influence of time-dependent motion on the mean state under otherwise similar flow conditions and model physics. The schematic below shows the mean flow of Antarctic Bottom Water in the deep basin with a steady deep western boundary current. Consistent with traditional models of deep circulation driven by large-scale upwelling, the dominant circulation features are the northward flowing deep western boundary current and a large-scale cyclonic (clockwise in the Southern Hemisphere)



Schematic of the mean circulation of Antarctic Bottom Water from the model with a steady deep western boundary current. Colored lines indicate bottom water depth (yellow for shallow, red for deep) while arrows indicate flow direction. The bold blue arrows show where the water flows into and out of the basin. Most of the water is carried to the north over the sloping bottom along the western boundary in the deep western boundary current. There is a cyclonic (clockwise) recirculation with a depressed center in the basin interior.