

Some Examples of Topographic Influence on the Abyssal Circulation

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Abstract. Three different geographical regions are discussed where it would appear that topography might play a major, if not dominant, role in the dynamics of the deep circulation. In the Gulf Stream recirculation, although topography does alter the distribution of potential vorticity, especially if considered in a two layer analogue, the eddies resulting from instability of the stream can homogenize the potential vorticity and give rise to intense recirculations. On the other hand the configuration of the western margin topography brings the Deep Western Boundary Current into contact with the Gulf Stream at Cape Hatteras. In attempting to negotiate this intersection and conserve potential vorticity the Deep Western Boundary Current must flow with the stream as it goes into deeper water before being able to escape to the south. Finally, an ambitious international WOCE program known as the Deep Basin Experiment, presently being carried out in the Brazil Basin, is described and some preliminary results shown. For the deeper layers topography isolates the Antarctic Bottom Water except for connecting flows to neighboring basins through a small number of passages.

Introduction

Although the upper ocean general circulation seems, for the most part, to be unaware of the bottom topography except through the constraints of the lateral boundaries the deep circulation is profoundly affected by the extensive undersea ridge systems as well as the configuration of the continental margins. Herein we will describe recent observations of the deep flow in two areas: the region near the Gulf Stream in the North Atlantic and the Brazil Basin of the South Atlantic.

Recirculations and Topography

It has been known for some time that the transport of the Gulf Stream increases by a factor of 5 from the Florida Straits to its maximum near 60°W downstream of Cape Hatteras (e.g., Knauss, 1969; Johns et al., 1995) and that this increased transport (and associated decrease) implies a vigorous recirculation system flanking the stream. It now appears that there are at least two recirculation gyres of opposite circulation sense and roughly equal intensity, one to the north of the stream and the other to the south.

Various explanations exist for this phenomenon ranging from buoyancy forcing (Huang, 1990) to eddy forcing (e.g., Cessi et al., 1987) to purely inertial dynamics (e.g., Marshall and Nurser, 1986; Hogg and Stommel, 1985). Considering the stratification to be modeled in a two layer system with the thermal wind shear of the Gulf Stream causing the lower layer to "outcrop" along its northern edge, Hogg and Stommel (1985) were able to show that the combined effect on the lower layer thickness of the thermocline and bottom depth changes could create a region of closed potential this to be homogenized by eddy stirring and that zonal

scales are much longer than meridional, they were able to vorticity contours to the north of the stream. Assuming develop an analytic model which predicted the right order of magnitude of the transport, approximately 30 Sv. Of course, in the presence of dissipation there must be some forcing.

Attempts to model this process numerically have been made and support the notion that the deep part of the recirculation is inertial. Malanotte-Rizzoli et al. (1995) simulate the forcing of the northern gyre through use of a boundary condition along a southern boundary which attempts to mimic the action of Gulf Stream meanders in a barotropic model. Only when the geometry contains closed potential vorticity contours for the ambient field does a vigorous recirculation emerge. In a more realistic barotropic model containing an unstable jet Jayne et al. (1995) find that closed potential vorticity contours arise naturally through the stirring action of the eddies arising from the instability of the jet, even without forcing the issue through distortions of the bottom topography. Hence it would seem that the particular shape of the bottom topography is not essential for forcing recirculations although it can help.

In the Synoptic Ocean Prediction Experiment (SYNOP) several eddy resolving arrays have been deployed across the stream at locations from near Cape Hatteras to just west of the Grand Banks. These data have been used to estimate eddy vorticity fluxes by Hogg (1993) who shows that the deep recirculation is nearly inertial and that the deep potential vorticity is nearly uniform. This flow is maintained against dissipative losses by an eddy "thickness flux" in the manner of Holland and Rhines (1980). The depth averaged flow is not inertial but is driven by lateral eddy vorticity fluxes.

Deep Western Boundary Current— Gulf Stream Crossover

At Cape Hatteras the Gulf Stream from the south intersects the DWBC flowing from the north. Hogg and Stommel (1985), using similar potential vorticity arguments to those for the recirculation, suggested that the DWBC would have to flow with the Gulf Stream into deeper water before being able to completely cross underneath it. It is becoming clearer that the DWBC is a multicomponent system with water derived from different source locations (Pickart, 1992) and evidence now suggests that the simple Hogg and Stommel model is a very crude approximation. Tracer measurements show that the shallower components are most affected by the stream, not surprisingly, and are swept downstream with it. The deepest components appear to make the crossing with only a modest change in depth (Pickart, 1992). This process has been recently modeled with good qualitative accuracy by Spall (1995) with a three layer model.

Brazil Basin

As part of the World Ocean Circulation Experiment an international investigation of processes important to the deep circulation, known as the Deep Basin Experiment (DBE), has been underway in the Brazil Basin. Objectives include quantification of the circulation within the three major water masses, Antarctic Intermediate Water, North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW), distinguishing between boundary and interior cross isopycnal processes, and understanding how the passages connecting the Brazil Basin to other deep basins might affect the water flowing through them. The field program has a number of elements including conventional hydrography, tracer measurements and current meter arrays. It also includes releases of a large number of neutrally buoyant floats within each water mass so as to observe directly the circulation and a deliberate tracer release to estimate cross-isopycnal mixing rates.

As the program is underway there is little concrete information available to address these objectives. In order to gain confidence in the neutrally buoyant floats, called RAFOS, which were commercially fabricated for the first time, a number were released for shorter periods than the ultimate design objective of 2.5 years. Trajectories from these early floats are shown in Figure 1. Although these are all less than 400 days in length they indicate a flow which is predominantly zonal with considerable low frequency variability. The zonal aspect is surprising as classical pictures of the flow at this NADW level suggest a meridional flow, southward near the boundary and a northward return flow offshore. It is entirely possible that the more complete set of trajectories available at the end

of the DBE will support this by showing a motion with large amplitude zonal sloshing and a slow meridional migration.

The deepest water masses flowing into the Brazil Basin are confined within the basin by the surrounding ridge system through which there are just four important gaps—the Vema and Hunter Channels on the southern boundary, the Romanche-Chain fracture zones at the equator in the Mid-Atlantic Ridge, and an equatorial passage (unnamed) farther west which permits leakage into the western North Atlantic. The transport of water through these passages has been fairly accurately estimated by use of moored current meter arrays in the DBE and it appears that there is an excess of about 4 Sv of AABW entering from the south over that leaving to the north. As the only escape for this water, assuming steady state, is a rise upward across isopycnals this indicates a basin averaged mixing rate of about 5 cm²/sec, substantially larger than rates measured in the thermocline elsewhere (Hogg et al., 1982).

Where this mixing is occurring is presently unknown but there will be two tracer releases in the deep water within the basin, one in the interior and the other near a

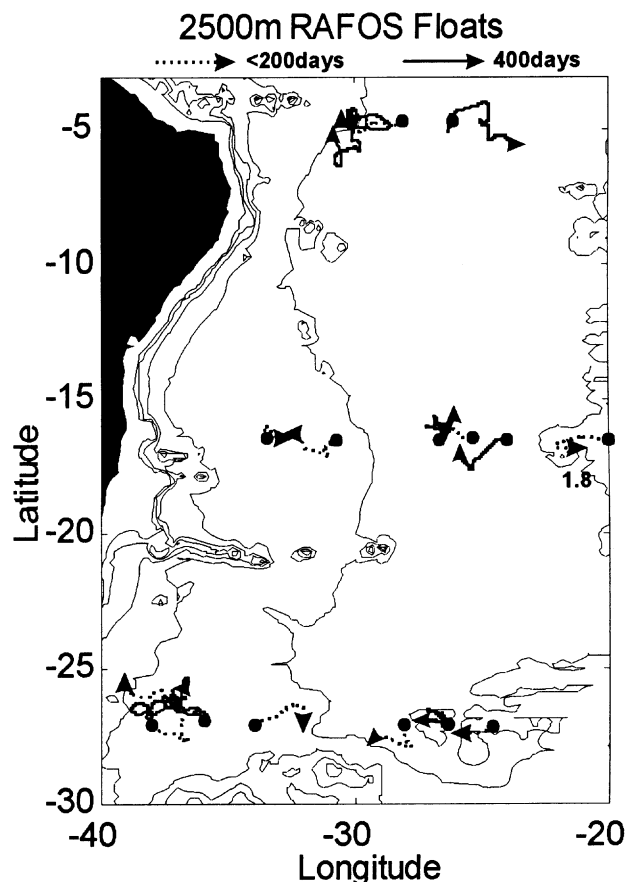


Figure 1. Trajectories of neutrally buoyant floats set near 2500 m depth within the NADW. These vary in length from less than 200 to 400 days.

boundary to help settle this issue. From a moored array in the Vema Channel we calculate cross-channel heat fluxes which would support a cross-isopycnal diffusivity of $50 \text{ cm}^2/\text{sec}$ if they were not neutralized by a compensating vertical flux. Such a diffusivity, if distributed all along the western boundary would account for the basin averaged value quoted above.

Summary

We have explored the deep circulation in three regions where the large scale bathymetry might be expected to be important to the lowest order dynamics. In the Northern Recirculation Gyre of the Gulf Stream, several studies have suggested that the geometry formed by the bight between the Grand Banks and Cape Hatteras, combined with the slope of the thermocline, could create regions of closed potential vorticity contours which would be favorable for formation of closed circulations. Numerical experiments suggest that this is not necessary and that the eddy fluxes associated with the instability of the stream can homogenize the potential vorticity and give rise to such recirculation zones. At Cape Hatteras itself, topography is clearly important in determining the manner in which the DWBC negotiates its intersection with the stream. Finally, early results from the Deep Basin Experiment suggesting that the subthermocline flow is primarily zonal are at odds with both published circulation schemes based on hydrography and the classic model of Stommel (1957). This may indicate that cross-isopycnal mixing processes are weak in the interior and this is consistent with crude estimates obtained from moorings in the Vema Channel.

Acknowledgments. This work has been supported by the National Science Foundation (OCE 90-04396 and OCE 90-04864) and the Office of Naval Research (N00014-90-J-1465).

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