The Damping Effect of Bottom Topography on Internal Decadal-Scale Oscillations of the Thermohaline Circulation

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ABSTRACT

By comparing the response of flat and bowl-shaped basins to fixed heat fluxes of various magnitudes, it is determined that coastal topography has a considerable damping influence upon internal decadal oscillations of the thermohaline circulation. It is proposed that this is because the adjustment of baroclinic currents to the no-normal-flow boundary condition at weakly stratified coasts is aided in the topography case by the generation of substantial barotropic flow.

1. Introduction

Analysis of the Comprehensive Ocean–Atmosphere Data Set has revealed interdecadal variations of North Atlantic sea surface temperatures seemingly unforced by contemporaneous atmospheric anomalies (Kushnir 1994). An interdecadal mode of variability involving the thermohaline circulation has also been found in a coupled ocean–atmosphere simulation (Delworth et al. 1993). Ocean-only models forced with mixed boundary conditions (Weaver and Sarachik 1991; Yin and Sarachik 1995) and fixed flux boundary conditions (Chen and Ghil 1995; Greatbatch and Zhang 1995; Huang and Chou 1994) also exhibit robust decadal-scale variability related to the thermohaline circulation.

Since the goal of the modeling activity is to understand nature, connections must be made between the modeled and natural variability. The mechanism of the variability is key to making this connection. The ocean-only experiments, because of their relative simplicity, should be useful for isolating the mechanism. Then, if the same mechanism is active in nature, these experiments may help distinguish variability that is inherently oceanic from that which is forced by the atmosphere or inherently coupled.

The recent finding of the internal decadal-scale variability in models forced only with fixed buoyancy fluxes allows for the possibility that this kind of variability is not truly thermohaline (i.e., does not involve the interplay of heat and salt). The fixed flux experiment is a simplification of the original mixed boundary conditions experiment that retains the timescale of the original variability as well as the prominence of slow boundary-propagating disturbances (Greatbatch and Peterson 1996, hereafter GP). The former experiment is obtained from the latter by fixing the heat as well as the salt flux. Assuming a linear equation of state (its nonlinearity is not important here), the problem can be recast in terms of a single buoyancy variable.

The original explanation for the fixed flux variability was that it was a sort of ''lurching'' phenomenon (Chen and Ghil 1995; Greatbatch and Zhang 1994; Huang and Chou 1994): When a dense anomaly is in the sinking region, it accelerates the overturning, casting up a buoyant anomaly, which subsequently retards the overturning to the point where the fixed buoyancy fluxes convert it to a dense anomaly once again. This meridional-plane argument is not supported, however, by meridional-plane frictional models, which do not produce oscillations even with very large fixed flux forcing (Winton 1996). These two-dimensional models do reproduce the millennial and centennial variabilities also found in three-dimensional models.

Experiments with rotating models indicate that convective adjustment and β are not critical to the variability. Work with various f-plane configurations suggests that *forcing of thermal wind currents normal to weakly stratified coasts* is the essential element needed to produce the oscillation (Winton 1996). Caution is warranted here because the adjustment of these currents to the no-normal-flow boundary condition gives rise to peculiar features in the flat-bottom model solutions that

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are not observed in the actual ocean, including large upwelling of dense and downwelling of buoyant water adjacent to high-latitude coasts. This thermally indirect circulation is an attempt by the model to adjust to the no-normal-flow boundary condition by distorting the stratification so as to build up a pressure gradient normal to the coast. Since the models make their own deep water, the stratification vanishes at high latitudes and the adjustment becomes problematic.

If the mechanism for the variability does, in fact, involve the adjustment of thermal wind currents to the no-normal-flow boundary condition in weakly stratified regions, it should be sensitive to the inclusion of coastal topography, which fundamentally alters this adjustment. This has been found to be the case in mixed boundary condition experiments. Moore and Reason (1993) and Weaver et al. (1994) found that their models oscillated with flat bottoms but were steady when topography was included. In this paper we seek to reproduce this sensitivity in fixed-flux experiments and understand it in terms of the oscillation mechanism offered by Winton (1996).

The next section presents the model to be used in this study. Following that, a comparison of the circulation in flat and bowl-shaped basins is made with emphasis upon the coastal adjustment. In section 4 the susceptibility to oscillation of the two geometries is compared. Section 5 presents the conclusions.

2. The model

The ocean model used in this study is the GFDL MOM 2 primitive equation model (Pacanowski 1995). The model is configured with 3° by 3° horizontal resolution and 15 vertical levels. The basin is a sector extending from 6° to 66°N and is 66° wide in the zonal direction. Conventional values are chosen for the diffusivities and viscosities: The diffusivities are 10^{-4} m^2 s^{-1} (vertical) and 10^3 m^2 s^{-1} (horizontal), and the viscosities are 2×10^{-3} m^2 s^{-1} (vertical) and 10^5 m^2 s^{-1} (horizontal). No wind stress or haline forcings are applied to the models. Two kinds of thermal boundary conditions are employed: restoring and flux. The restoring nudges the top 52-m grid layer to the temperature profile

$$T_{\rm ref}(\phi) = 20 \times \frac{66 - \phi}{60} \qquad (1)$$

on a 50-day timescale (ϕ is latitude in degrees). Under the flux forcing, a fixed heat flux

$$F(\phi) = F_{\rm o}\left(\cos\frac{\phi - 6}{60}\pi - \overline{\cos\frac{\phi - 6}{60}\pi}\right) \qquad (2)$$

is applied to the top grid layer. The overbar denotes averaging over the area of the basin—this term ensures

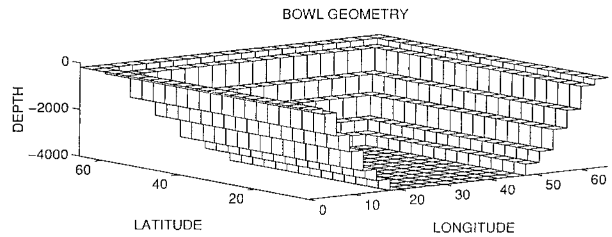

FIG. 1. Basin geometry for the BOWL experiments. BOX experiments have the same perimeter but a flat bottom at 4000 m.

a zero net heat flux. The standard MOM 2 equation of state was replaced with the linear form:

$$\rho(T) = -2 \times 10^{-4}T. \qquad (3)$$

The model is formulated with two bottom topographies: 1) a flat bottom (the ''BOX'' experiments) and 2) a bottom with sloping walls along the western, eastern, and northern boundaries (the ''BOWL'' experiments). Figure 1 shows the bottom topography for the BOWL experiments. The slope takes nearly 20° to reach bottom. This is considerably more gentle than the typical continental slope but compares to the gradual upward slope encountered by the North Atlantic Current as it flows northward toward Iceland and Greenland. The goal here is to investigate the qualitative effect of sidewall topography, and for that purpose a slope that is well resolved by the coarse model grid was chosen.

3. Circulation with and without bottom topography

First, we examine the steady states produced by forcing the two models by restoring surface temperatures to the reference profile (1). The solutions are remarkably different in many respects. Figure 2 shows the surface pressure for the two solutions. Since there is no wind forcing, the contours are very nearly streamlines of the surface flow. The flow is particularly different in the high latitude part of the basin. The BOX geometry has a broad east bearing jet fed by upwelling along the western boundary and feeding intense downwelling on the eastern boundary. In the BOWL geometry, the flow forms a cyclonic gyre. The downwelling in the east is much reduced and the upwelling in the west is eliminated north of 40°N. The BOWL circulation western boundary current separates from the coast in an intense jet near 35°N.

Figure 3 shows the meridional overturning streamfunction for the two geometries. The BOX overturning has a maximum streamfunction of 18 Sv (Sv ≡ 10^6 m^3 s^{-1}). At high latitudes, this is primarily the projection onto the meridional plane of the quasi-zonal circulation shown in Fig. 2. The BOWL geometry has only 6 Sv of overturning, and the node is positioned at the base

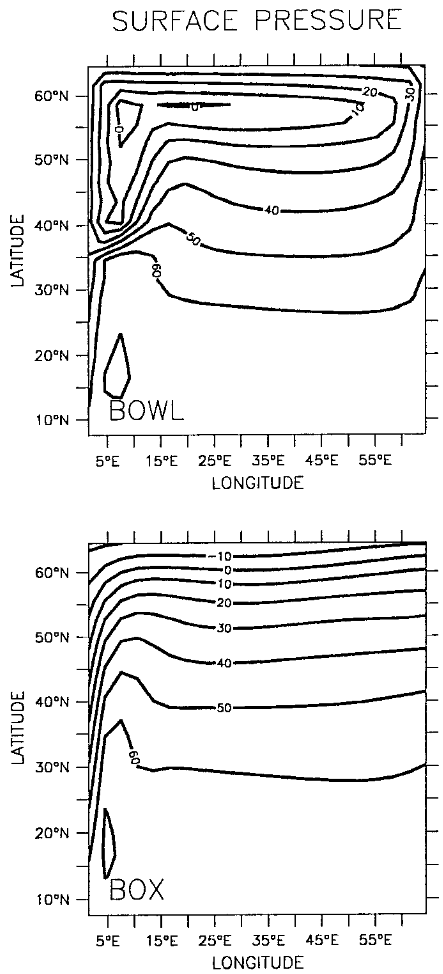

FIG. 2. Surface pressure for the BOX and BOWL geometries expressed in equivalent surface height (10^{-2} m). Bottom topography greatly reduces the alongshore pressure gradients at high latitude.

of the thermocline rather than at middepth as in the BOX case.

Figure 4 shows the barotropic streamfunction for the BOWL geometry. The BOX geometry circulation is almost purely baroclinic, so its barotropic streamfunction is not shown. Since the momentum advection terms are negligible, bottom pressure torque is responsible for the gyre flows seen in the figure. With bottom topography, the high-latitude thermohaline circulation is more in the horizontal plane than in the meridional plane—there are 14 Sv of barotropic flow and only 6 Sv of meridional flow.

It is apparent from the changes in circulation that the adjustment of the high-latitude baroclinic jet to the no-normal-flow boundary condition is eased by the presence of topography. Why should this be so? Imagine the adjustment of a rotating two-layer fluid with a free surface to a boundary parallel to the interface height gradient. If the bottom is flat, the flow is nearly baroclinic and surface height is just a rescaled mirror image of the interface height—the free surface does not help to bring the cross-shore flow to zero because its gradient also parallels the coast. If there is bottom topography with a cross-shore slope, the cross-shore component of the bottom flow directly modulates the free surface

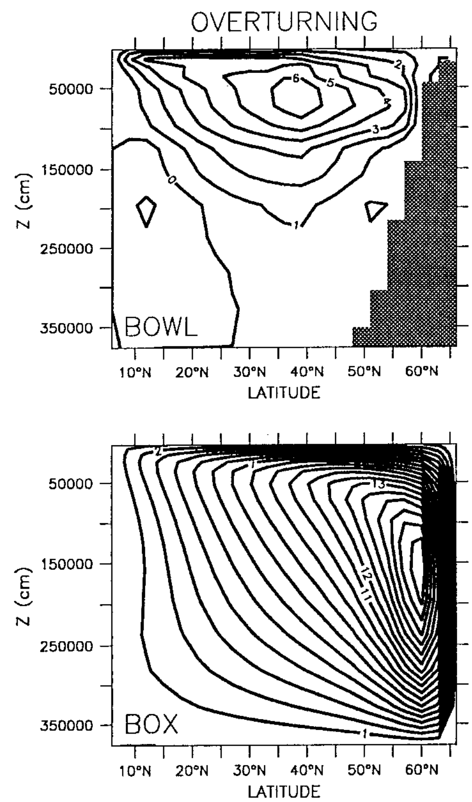

FIG. 3. Zonally integrated circulations for the BOX and BOWL geometries (units are 10^6 m^3 s^{-1}).

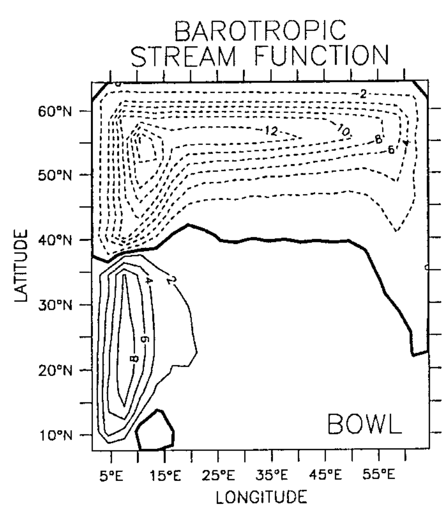

FIG. 4. Vertically integrated circulation for the BOWL geometry (units are 10^6 m^3 s^{-1}).

TABLE 1. Potential to kinetic energy conversion (10^{-6}g cm^{-1} s^{-3}).

Geometry	Baroclinic	Barotropic	Total
Bowl	0.5	1.9	2.4
Box	1	0	1

height through net water column divergence. The free surface and the interface height become decoupled and the former can be distorted so as to build up a cross-shore pressure gradient.

In the rigid-lid models, of course, there is no deformation of the upper surface. Instead, energy that would have gone into free surface deformation is converted directly from potential to kinetic energy of the barotropic mode through bottom pressure torque. Table 1 shows the difference in potential to kinetic energy pathways for the BOX and BOWL geometries. In the BOX geometry all of the energy goes into the baroclinic mode. In the BOWL geometry the conversion into the barotropic mode is almost four times that going into the baroclinic mode, and the total energy conversion is 2.4 times greater. The kinetic energy of the BOWL circulation is almost twice that of the BOX circulation (0.57 erg cm^{-3} vs 0.31 erg cm^{-3}).

The cyclonic subpolar circulation of Fig. 4 corresponds to a feature of the North Atlantic Circulation deduced from hydrography and wind stress data. Greatbatch et al. (1991) solve the barotropic vorticity equation using climatological data and find 30 Sv of cyclonic bottom torque driven circulation in this region (their Fig. 6). Thus, the inclusion of coastal topography adds a realistic feature to the circulation and removes some unrealistic features (large vertical velocities on the boundary).

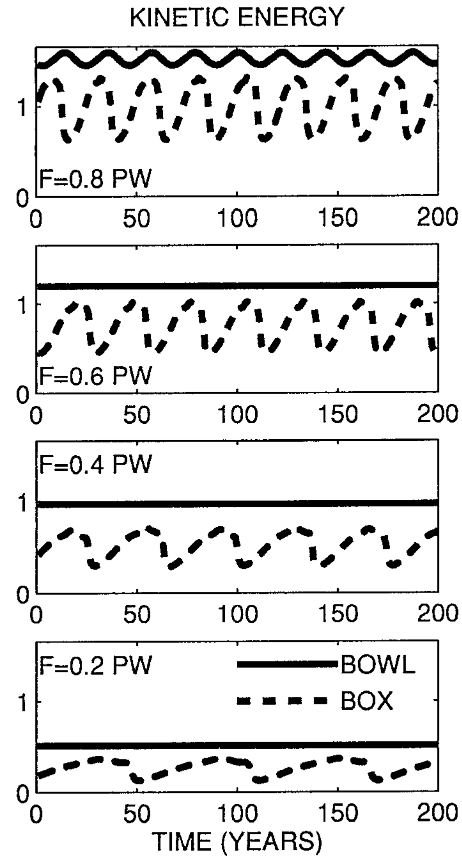

FIG. 5. Kinetic energy of the BOX and BOWL geometries under fixed heat fluxes of various magnitudes (units are 10^{-1} kg m^{-1} s^{-2}).

4. The effect of bottom topography upon variability

Now we switch from the restoring boundary condition of the last section to the fixed-flux form (2) in order to determine the susceptibility to oscillation of the BOX and BOWL basins. The fixed-flux boundary condition is not used because it is a better representation than the restoring boundary condition of surface forcing in the actual ocean (it is not). Rather, it is used here because 1) it allows us to make a fair side by side comparison of the models by applying the same fluxes to both and 2) it is a nondamping boundary condition that allows the models maximum freedom to develop internal variability.

In spite of the striking differences between the BOX and BOWL circulations described in the last section, they transport nearly the same amount of heat poleward, about 0.2 PW (1 PW = 10^{15} W). In (2) F_o is adjusted to put this amount of heat into the basin at low latitude and take it out at high latitude. Figure 5 shows the result of forcing both geometries with this boundary condition and also with the fluxes doubled, tripled, and quadrupled. The BOX geometry solution is oscillatory for all of the forcing levels. As the forcing becomes stronger, the oscillations increase in frequency and amplitude. The BOWL geometry solution is steady for the standard, doubled, and tripled forcing. The BOWL oscillation induced with quadrupled forcing is much smaller in amplitude than the BOX oscillation under that forcing or even the BOX oscillation under the standard forcing. Whether the measure of susceptibility to oscillation is the critical forcing level required to induce oscillation or the amplitude of oscillation at a fixed level of forcing, the BOWL is substantially less oscillatory than the BOX.

In addition to having a smaller amplitude, the BOWL oscillation is qualitatively different than the BOX oscillations. The most prominent aspect of the BOX oscillations is the growth and decay of disturbances that propagate cyclonically around the basin [see Winton (1996) and GP, for further description]. The BOWL oscillation involves a slight expansion and contraction to the west of the convecting region at 55°N in the core of the subpolar gyre (Fig. 6). It is perhaps not so surprising that a stagnant region in the flow develops time

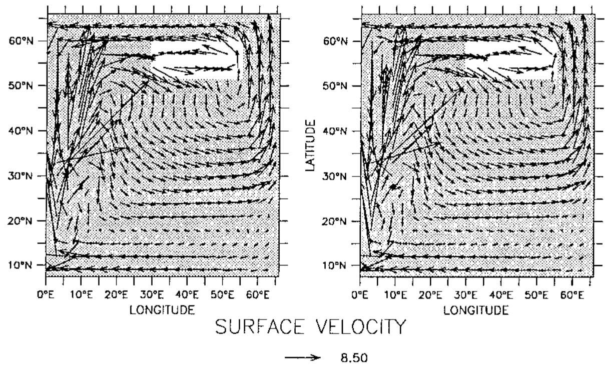

FIG. 6. Extreme phases of the BOWL oscillation cycle. The convecting region at 55°N in the core of the subpolar gyre (unshaded) is expanded slightly to the west in the left panel. Velocity units are 10^{-2} m s^{-1}.

dependence to balance the imposed surface flux when it reaches a sufficient magnitude. Since the meridional scale of the variability is a single grid cell, an accurate parameterization for subgrid-scale horizontal mixing would be needed to assess its realism.

These results might support a claim that the bottom pressure torque, found in the last section to be such an important driver of the horizontal circulation in the BOWL basin, has a suppressive effect upon the oscillations. An alternative hypothesis, however, might emphasize the thermodynamic effect of bottom topography over this dynamic effect. Since the bottom shoals to the north in the BOWL basin, thermal wind currents normal to the coast may be weaker, reducing the forcing of coastal anomalies. To help distinguish the dynamic and thermodynamic effects two of the experiments were repeated in a ''modified BOWL'' basin. This basin has the same meridional bottom slope as found at the middle longitude of the full BOWL basin but no bottom slope in the zonal direction. Thus, the fixed flux forcing does not directly generate bottom pressure torque in this basin although there will in general be some generation of torque by currents that are not aligned with the forcing. Thus, the modified BOWL basin emphasizes the thermodynamic effect of the bottom topography at the expense of the dynamic effect.

When the modified BOWL basin was forced with F_o = 0.2 PW (corresponding to the bottom panel in Fig. 5), the solution became steady after a period of damping oscillations. Increasing F_o to 0.4 PW produced self-sustaining oscillations, considerably larger in amplitude than those of the BOX basin under the same forcing. The modified BOWL experiments had some bottom pressure torque-driven barotropic flow, although less than in the full BOWL geometry. Although it is impossible to distinguish the thermodynamic and dynamic effects completely, these experiments suggest that the thermodynamic effect of the bottom shoaling to the north has a lesser impact upon the oscillatory nature of the model than the generation of horizontal flow by bottom pressure torque.

5. Conclusions

The experiments of the last section indicate that flat-bottom models may overestimate the internal decadal-scale variability of the actual thermohaline circulation. This is because their variability arises out of the considerable difficulty they have adjusting baroclinic currents to the no-normal-flow boundary condition at weakly stratified coasts. The adjustment is made easier by the presence of coastal topography, which decouples the free surface from the baroclinity or, in terms of the rigid-lid problem, allows conversion of potential energy directly into the barotropic mode. This conversion pathway dominates the conversion into baroclinic kinetic energy in the basin with coastal topography. Since the barotropic mode is trivially adjusted to the no-normal-flow boundary condition through lid pressure adjustment, the problem is greatly reduced.

Winton (1996) argued that the propagating anomalies of the flat-bottom model oscillations are formed in the northeast corner (the boundary between stratified and unstratified fluid) by a thermally indirect circulation that intensified the baroclinity of the onshore jet. It is consistent with this mechanism that the oscillations are greatly inhibited in the BOWL circulation, which does not have either the onshore jet or significant thermally indirect circulation at high latitudes. Furthermore, that the mixed boundary condition models (Moore and Reason 1993; Weaver et al. 1994) exhibit the same sensitivity to topography as the fixed flux boundary condition model used here argues for a single mechanism underlying the internal decadal variabilities of both.

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