Meridional Overturning as a “Pump and Valve” System

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Abstract. A three-dimensional analytical model of meridional overturning in a basin with a southern-hemisphere circumpolar connection is presented. The overturning circulation can be understood as a “pump and valve” system, in which the wind forcing at the latitudes of the circumpolar connection plays the role of the pump, and the surface thermodynamic exchange north of the connection plays the role of the valve. When the surface fluxes support deep-water formation, the valve is on, and the overturning circulation extends to the extreme northern latitudes of the basin. When the surface fluxes do not support deep-water formation, the valve is off; in that case, the basin north of the circumpolar connection fills to the sill depth with warm fluid, and the overturning circulation still exists, but is short-circuited and confined near the circumpolar connection. An intriguing implication of the model is that northern hemisphere wind and surface buoyancy forcing may influence the strength and structure of the circumpolar current in the southern hemisphere.

Introduction

An important open question in physical oceanography, and one of the topics of this workshop, is whether and to what degree the ocean’s large-scale meridional overturning circulation is driven by near-boundary turbulence. By “near-boundary,” I mean near the bottom boundary, not the surface boundary layer, where wind-driven turbulence is known to play an important role. The answer to this question is closely related to the determination of the value of the appropriate mean empirical diapycnal turbulent diffusivity κ: is it of order 10^{-5} or 10^{-4} m^2 s^{-1} ?

Large-scale theory suggests that, to first order, turbulent diapycnal diffusion is needed to explain only one of the three large-scale meridional overturning cells that emerge in coarse conceptual syntheses of observations, the abyssal cell associated with the northward flow and subsequent upwelling, mixing, and southward return flow of Antarctic Bottom Water (AABW). The two upper cells, involving the warm wind-driven gyres and the southward flow of North Atlantic Deep Water (NADW), both arise naturally in theoretical models in which the large-scale wind stress drives the circulation, and thermohaline transformations occur only in regions that are exposed to surface forcing. Adiabatic or weakly diffusive theoretical models of the warm wind-driven gyres and the subtropical main thermocline have been discussed by *Veronis* (1973), *Luyten et al.*, (1983), *Samelson and Vallis* (1997), and others. I discuss here a simple, idealized, analytical model of a quasi-adiabatic mid-depth (“NADW-like”) meridional overturning cell, which extends a previous model (*Samelson*, 1999) of large-scale geostrophic circulation in an idealized Southern Ocean geometry. I believe that this model is relevant to recent ideas regarding the influence of southern hemisphere winds (*Toggweiler and Samuels*, 1995) and northern hemisphere surface buoyancy forcing (e.g., *Clark et al.*, 2001, and references therein) on the global meridional overturning circulation. The third, abyssal cell is likely best understood essentially as a diffusively-driven circulation of the type envisioned by *Stommel* (1958), extended to account for spatially variable turbulent mixing and complex bathymetry.

It is worth noting that this qualitative theoretical picture is generally consistent with recent large-scale observational analyses (e.g., *Schmitz*, 1996a,b; *Sloyan and Rintoul*, 2000, 2001ab), which tend to indicate that upwelling through the main thermocline and the upper part of the deep thermocline is small equatorward of the subpolar gyres and the Antarctic Circumpolar Current (ACC), and that $\kappa \approx 10^{-5}$ m^2 s^{-1} is likely sufficient to balance the observed upwelling in these regions. Larger diffusivities may be required at abyssal depths and in the lower part of the deep thermocline. As pointed out, for example, by *Webb and Suginohara* (2001), there seems to be little need to assume an upwelling volume flux of 30×10^6 m^3 s^{-1} through the mid-depth thermocline equatorward of the subpolar gyres, although some authors have argued otherwise.

The Gill-Bryan Geometry: The Pump

Gill and Bryan (1971) studied the circulation in a large-scale (technically primitive-equation, but effectively planetary geostrophic, because of the coarse resolution) numerical model with a circumpolar connection. The idealized basin geometry consisted of a rectangular box with vertical sidewalls, with gaps near the southern ends of the eastern and western boundaries, at which periodic boundary conditions were imposed to represent the circumpolar connection through Drake Passage in the Southern Ocean. The model circulation was found to depend strongly on the presence of the gap and the depth to which it extended.

Samelson (1999) offered a simple analytical theory for the steady planetary geostrophic circulation in the Gill-Bryan geometry, for a specific form of wind and thermal forcing relevant to the southern hemisphere oceans: wind-driven upwelling south of the gap, surface heating and uniform Ekman transport northward across the gap, and downwelling at subtropical southern-hemisphere latitudes north of the gap. Briefly, this theory and the resulting model ocean thermal structure and circulation patterns (Fig. 1) have the following characteristics:

- The circumpolar connection prevents net meridional geostrophic flow across the gap at depths above the sill, so meridional flow across the gap must occur either ageostrophically in the surface Ekman layer or geostrophically beneath the sill;
- A thermal circumpolar current arises in response to the imposed surface heating and northward Ekman transport, as the basin north of the gap fills with warm fluid to the depth of the sill, where the return geostrophic flow can be supported;
- The return flow in the deep geostrophic boundary current beneath the sill is cooled by convection as it crosses the gap latitudes;
- The transport of the model circumpolar current depends on the imposed surface thermal gradients and the gap geometry, but not on the strength of the wind forcing (provided that this forcing does not vanish).

Thus, the meridional circulation cell in this model consists of wind-driven upwelling south of the gap ($y < -0.8$ in Fig. 1), northward surface Ekman transport across the gap to the subpolar-subtropical gyre boundary ($y = -0.6$), Ekman downwelling in the subtropical gyre ($-0.6 < y < -0.4$), and southward western boundary current transport from the subtropical gyre to the gap and then across the gap beneath the sill. The Ekman transport northward across the gap can be thought of as a pump, which forces the fluid up the surface dynamic pressure gradient across the circumpolar current.

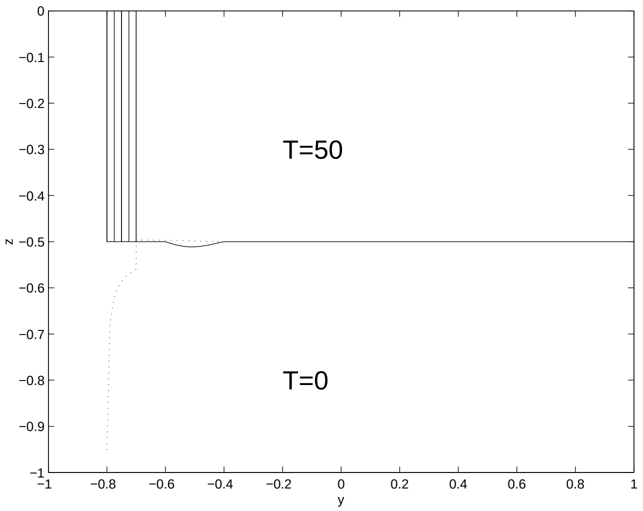

Figure 1. Meridional-vertical cross-section of thermocline structure when the valve is off (after *Samelson*, 1999). Contours of temperature, nondimensionalized as in *Samelson* (1999), at the western edge of the basin interior (solid lines) and the depth of the warm layer at the western boundary (dotted line) are indicated. The gap (circumpolar connection) is located in the region $-0.8 < y < -0.7$, $-0.5 < z < 0$, where latitudinal distance has been scaled by 5000 km and depth by 5 km. The central latitude ($y = 0$) is the equator.

Presumably, this theory is relevant to the numerical solutions obtained in similar geometries by *Gill and Bryan* (1971), *Toggweiler and Samuels* (1998), *Vallis* (2000) and others; however, the specific form of the wind and thermal forcing assumed by *Samelson* (1999) precluded a direct comparison. The purpose of the present contribution is to outline how this theory can be extended to include a northern-hemisphere basin with surface cooling and deep-water formation at the extreme northern latitudes. The resulting meridional overturning cell represents a simple analog of (part of) the mid-depth cell associated with NADW formation and circulation in the North Atlantic.

Northern-Hemisphere Cooling: The Valve

The thermal and wind forcing imposed north of the circumpolar connection in the model of *Samelson* (1999) was extremely simple, consisting of a uniform surface temperature at all latitudes north of the gap, and an effective zonal wind stress that was constant immediately north of the gap, decreased smoothly to zero in the southern subtropics, and remained zero at all points farther north. This, of course, differs substantially from the wind stress and surface buoyancy forcing to which the modern global ocean is subjected at latitudes north of the ACC. The purpose of the present note is to explore the consequences of including in this model a simple representation of observed cooling at extreme northern latitudes. Indeed, as noted below, it will appear that it would be relatively straightforward also to include a representation of subtropical and equatorial heating and wind forcing, following classical ventilated thermocline theory (*Luyten et al.*, 1983) and its equatorial extensions (e.g., *Pedlosky and Samelson*, 1989), but this is left for future work.

The simple representation of northern-latitude cooling considered here is an imposed conversion of warm fluid to cold fluid in the northern subpolar gyre. This specification purposely avoids the details of precisely how and where the conversion takes place. Continuity of boundary currents and pressure gradients across the equator is assumed. The resulting model circulation clearly will be sensitive to the imposed rate of conversion and to the conversion temperature. In order to maintain a steady state in the quasi-adiabatic limit, however, the rate of conversion must match the rate of production of warm fluid. In the present case, this production is set by the northward Ekman transport across the southern-hemisphere gap. If the conversion is less than this transport, the warm fluid will accumulate north of the gap, until the sill depth is reached, as in the original case illustrated in Fig. 1. Thus, the conversion rate can be thought of as a valve, which controls the flux out of the warm layer, where the dynamic surface pressure is maximum.

The choice of conversion temperature is also important. For simplicity, this is chosen in the present model so that the fluid is cooled in the northern hemisphere by half the difference between the surface temperatures north and south of the southern-hemisphere gap. Thus, the cooled fluid will have a temperature equal to the median of the maximum and minimum temperatures in the basin. With the nondimensionalization as in *Samelson* (1999), the minimum temperature is $T = 0$, the maximum temperature is $T = 50$, and the warm fluid is cooled to $T = 25$ at the extreme northern latitudes of the northern-hemisphere basin (Fig. 2).

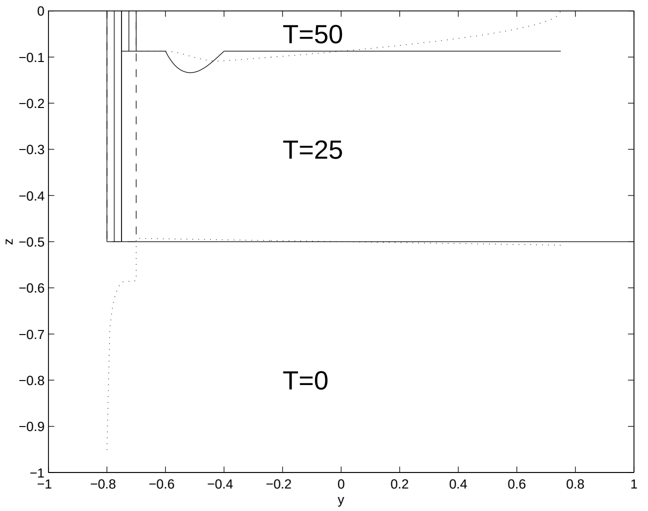

Figure 2. Meridional-vertical cross-section of thermocline structure when the valve is on. Geometry and contours as in Fig. 1, but schematic for the western-boundary warm-layer depths (dotted lines) north of the gap, and with the portion of the gap edge not coincident with an isotherm also indicated (dashed line). The upper interface is not shown in the northern-hemisphere subpolar gyre, where warm fluid cools and sinks.

With this northern cooling, the southward return flow occurs in the western boundary current of the intermediate layer, which in turn now must deepen to the sill depth. The deep return flow beneath the sill is colder than the surface fluid until it reaches the central latitude of the gap (where the surface temperature is $T_s = 25$), and thus does not induce convective exchange until it reaches this central latitude. Consequently, the structure of the thermal circumpolar current is no longer determined by the convective adjustment process north of this central latitude, and additional assumptions or dynamics are necessary to obtain a unique solution. One choice, illustrated in Figure 2, is to extend the surface temperatures in this region downward to the depth reached by the warm layer on the north side of the gap. Alternatively, the intermediate-layer ($T = 25$) fluid could be extended upward all the way to the surface. In any case, it is interesting to note that, in this model, northern-hemisphere cooling has a direct effect on the strength and structure of the circumpolar current.

The depth of the warm layer north of the gap must now also be determined, since it is no longer related to the sill depth . A simple and reasonable constraint that achieves this is to choose the eastern-boundary depth of the warm layer just large enough to support northward flow in the western boundary current from the subtropical to the subpolar gyre in the northern hemisphere, with volume flux equal to the northward Ekman transport at the northern edge of the southern-hemisphere gap. This completes the warm-to-cold pathway of the meridional cell; without this flow, the warm source-water would not reach the subpolar gyre, and the warm layer would again deepen as the warm fluid accumulated north of the gap. If the western boundary current is assumed not to separate from the boundary, then this eastern boundary depth can be calculated by requiring the warm layer to outcrop at the inshore edge of the boundary current at the subtropical-subpolar gyre boundary, as indicated schematically in Figure 2. Because both layers are in motion in the western boundary current, the net meridional geostrophic transport in each layer is not simply proportional to the diffferences in the squares of the layer depths at the eastern and western boundaries as in *Samelson* (1999); to complete the analytical model, some additional specification of the horizontal structure of the geostrophic boundary currents would be necessary. It is interesting to note that the inclusion of wind-stress forcing in the northern hemisphere would presumably cause an additional increase in the eastern-boundary depth of the warm layer, to support geostrophic return flow of the southward Ekman transport out of the subpolar gyre (e.g., *Samelson and Vallis*, 1997). Under the present assumptions, this would also influence the strength and structure of the circumpolar current in the southern hemisphere.

In summary, the meridional circulation cell in this model consists of wind-driven upwelling south of the gap ($y < -0.8$ in Fig. 2), northward surface Ekman transport across the gap to the subpolar-subtropical gyre boundary ($y = -0.6$), Ekman downwelling into the warm ($T = 50$) layer in the subtropical gyre ($-0.6 < y < -0.4$), and northward western boundary current transport from the southern hemisphere subtropical gyre to the northern-hemisphere subtropical-subpolar gyre boundary ($y = 0.75$), followed by cooling and sinking into the intermediate ($T = 25$) layer in the northern subpolar gyre, and southward intermediate-layer return flow in the western boundary current to the gap and then across the gap beneath the sill.

Conclusions

In the context of the present workshop, the main point to be made with this model is that an analog of the NADW meridional overturning cell can be constructed in which there is no interior mixing at all: all the thermodynamic exchange occurs where the fluid is exposed to the surface forcing. This deep meridional cell can be understood as a pump and valve system, in which the wind-forcing at the latitude of the southern-hemisphere circumpolar connection plays the role of the pump, and the thermodynamic exchange in the northern-hemisphere subpolar gyre plays the role of the valve. When the valve is on, the fluid is cold and the surface dynamic pressure is low in the northern-hemisphere subpolar gyre, and the flow and thermocline structure are as in Figure 2. When the valve is off, the fluid is warm and the surface dynamic pressure is high in the northern-hemisphere subpolar gyre, and the flow and thermocline structure are as in Figure 1.

Of course, it should be borne in mind that this model contains a number of fundamental idealizations and simplifications. For example, mesoscale eddy processes in the Southern Ocean have been purposely neglected, while observations (e.g., *Speer et al.*, 2000) suggest that some of the southward NADW flow and subsequent upwelling into the ACC may occur above the levels at which topography can support southward geostrophic flow. Substantial thermohaline transformations clearly do occur in the deeper part of the NADW cell, associated in part with the diffusively-driven abyssal AABW cell; such interior mixing processes have also been purposely neglected in the present model.

On the other hand, the model has some appealing aspects, at least for pedagogical purposes. It provides an explicit analytical formulation of a conceptual model of one variety of overturning circulation that has been developed to varying degrees by previous authors (e.g., *Toggweiler and Samuels*, 1995; *Webb and Suginohara*, 2001). A shutdown, or short-circuiting, of the meridional overturning cell is indicated by this steady model when the valve is moved from on to off; such a shutdown of meridional overturning by the analogous introduction of a freshwater cap in the northern-hemisphere subpolar gyre has been previously found and studied in numerical models (e.g., *Stocker and Wright*, 1991). Unlike the circulation considered by *Samelson* (1999), the present model supports a northward ocean heat flux representative of that associated with the observed NADW cell (e.g., *Talley*, 2003), with surface heating at the gap latitudes in the southern hemisphere, and surface cooling in the subpolar gyre of the northern hemisphere. Note also that since all of the meridional transport in the intermediate layer ($T = 25$) occurs in the western boundary currents, the intermediate layer is at rest in the interior, and it would be straightforward to supplement this analytical model with additional warmer fluid layers representing a ventilated thermocline (*Luyten et al.*, 1983) in the subtropical gyres. It may be possible to explore some aspects of Antarctic Mode and Intermediate Water formation and circulation within the resulting framework, as the present warm-layer circulation may prove to be most closely related to these. A surprising implication of this model is that the northern-hemisphere wind stress and deep-water formation may affect the strength of the circumpolar current; this is an intriguing counterpoint to the recent suggestion (*Toggweiler and Samuels*, 1995) that southern hemisphere winds may control the northern-hemisphere deep-water formation rate. I am hopeful that further consideration of these and other related problems in the context of this contribution will lead to improved understanding of the mechanisms of meridional overturning in the global ocean.

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