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An Analogy to the Antarctic Circumpolar Current

Henry Stommel

*Harvard University
Cambridge, Mass., U. S. A.*

Introduction. In a survey article (Stommel 1957), the Antarctic Circumpolar Current was crudely pictured as a simple convergent poleward geostrophic flow at longitudes far removed from Drake Passage, with a higher order dynamical process through Drake Passage; however, no theoretical model was presented to describe analytically the nature of the flow through Drake Passage. There are difficulties in picturing the nature of the boundary conditions, especially along the western coast of the Palmer Peninsula where evidently something like an eastern boundary current is required to feed the flow through the Passage. The topic is obscure, and in an attempt to gain some understanding, an analogous situation, in the form of a laboratory experiment (as yet unperformed), is discussed in the following. Stommel *et al.* (1958) published an account (hereafter referred to as SAF) of studies made in a rotating basin, of nonuniform depth. An essential part of the experiments was the presence of at least one complete radial barrier. In the results obtained by Faller (1960) with no barrier, an entirely different regime occurs. The present study describes the transition from one regime to the other as a single complete radial barrier is gradually removed.

The Porous Barrier. In order to devise a very simple barrier which can be gradually removed, we make it porous, so that water can percolate through it with a zonal velocity v_{φ}^* governed by a resistance R and an equivalent to Ohm's law:

$$Rv_{\varphi}^* = g(\zeta_{\varphi=2\pi} - \zeta_{\varphi=0}), \quad (1)$$

with the asterisk denoting the velocity inside the porous wall and with the other quantities the same as in SAF. There is, generally, a difference in pressure across the wall.

For simplicity we fix a source S_1 distributed uniformly along the rim and a source S_0 at the center of the tank (actually S_0 is a sink, and hence negative)

so that there is no western boundary current when $R = \infty$. According to eq. 15 of SAF, the transport in the western boundary current can be made to vanish if

$$S_0 = -x S_1, \quad (2)$$

where

$$x = \frac{1}{1+l}. \quad (3)$$

Therefore, in terms of the source at the rim S_1 ,

$$S_0 = -\frac{1}{1+l} S_1 \quad (4)$$

and there is a uniform rate of rise of the free surface (eq. 7) given by

$$\dot{\zeta} = \frac{S}{\pi a^2} \quad (5)$$

where

$$S = S_0 + S_1 = \left(1 - \frac{1}{1+l}\right) S_1. \quad (6)$$

The radial component of velocity is obtained from SAF eq. 8:

$$v_r = -\frac{S}{2\pi h_0 l r}. \quad (7)$$

There is no tangential component of flow, v_φ . There is a pressure gradient in the angular direction, and the pressure difference across the solid wall ($R = \infty$) is calculated from eq. 3 of SAF:

$$g(\zeta_{2\pi} - \zeta_0) = \frac{2\omega S}{h_0 l}. \quad (8)$$

When $R < \infty$ there is a flow through the wall, and from (1)

$$v_\varphi^* = \frac{1}{R} g(\zeta_{2\pi} - \zeta_0); \quad (9)$$

if this is used as a boundary condition at the wall, we can extend it into the interior

$$v_\varphi = v_\varphi^*. \quad (10)$$

The isobars now, instead of being purely radial, spiral inward, as in Fig. 1: drawn for the case where $R = 4\omega a$. The computation from eqs. (2) and (3) of SAF yields

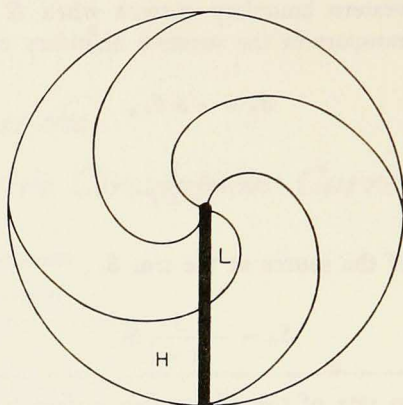


Figure 1. Flow pattern, showing spiral isobars of geostrophic currents in the interior. The sense of rotation is the same as in the northern hemisphere. The isobars are not continuous through the heavy black porous radial barrier.

$$g \frac{\partial \zeta}{\partial r} = 2 \omega v_{\varphi} = \frac{4 \omega^2 S}{R h_0 l} \quad (11)$$

$$g \frac{\partial \zeta}{\partial \varphi} = -2 \omega r v_r = \frac{\omega S}{\pi h_0 l} \quad (12)$$

The isobars lie along spirals with slope

$$\frac{\partial r}{r \partial \varphi} = \frac{R}{4 \pi \omega r} \quad (13)$$

There is the same drop in pressure across the wall as before. For a fixed S , more and more isobars appear as the resistance R is lowered, so that the pressure difference between the origin, $r = 0$, and the rim, $r = a$, increases. As $R \rightarrow 0$, this pressure difference, and the zonal velocities, tend to increase without limit. There is obviously a physical limit in an actual experiment, of course; for one thing we have neglected to introduce friction in the interior up to this point. For low viscosity and large R there is no important effect of friction. But as $R \rightarrow 0$ an appreciable fraction of the flow from the rim toward the center can be accomplished by cross-isobar flow: that is, within a thin bottom viscous Ekman layer instead of entirely as a radially directed component of geostrophic flow.

For convenience of calculation we will suppose¹ that the effect of viscosity in the interior does not become important until the zonal component of the geostrophic flow is many times the radial component, that is $R/4\omega a \ll 1$. The cross-isobar flow (measured positive out from the origin) is then essentially

¹ This can always be arranged experimentally.

radial, and proportional to the zonal geostrophic component only: $-\frac{\pi r}{r} v_\varphi$, where $\gamma = \sqrt{\omega/\nu}$, and ν is the kinematic viscosity. The total radial flow, $-Sh/h_0 l$, is made up of the sum of the radial geostrophic flow, $2\pi r h v_r$, and of the total radial cross-isobar flow, $-\pi r v_\varphi/\gamma$; thus we obtain the relation

$$2\pi r h v_r - \frac{\pi r}{\gamma} v_\varphi = -\frac{Sh}{h_0 l}, \quad (14)$$

and from eq. (11) and (12)

$$v_r = -\frac{R}{4\pi\omega r} v_\varphi, \quad (15)$$

and finally, eliminating v_r from (14) and (15),

$$\left[\frac{R}{2\omega a} + \frac{\pi r}{\gamma h a} \right] v_\varphi = \frac{S}{h_0 l a}. \quad (16)$$

It is clear that the role of bottom friction begins to be important as $R \rightarrow 0$ so that the zonal velocity approaches asymptotically the limit

$$v_\varphi \rightarrow \frac{\gamma h S}{\pi r h_0 l}. \quad (17)$$

The pressure gradient around the vessel is insensible to variations in R as long as the Ekman layer is unimportant, but when R is small enough to permit an important Ekman cross-isobar flow, the pressure gradient around the vessel decreases until, in the limit of vanishing resistance R , the isobars are closed concentric circles, and there is a zonal geostrophic flow just sufficient

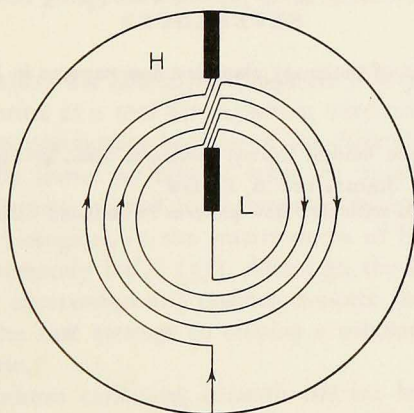


Figure 2. Flow pattern analogous to the Antarctic Circumpolar Current in a basin with partly porous wall. The sense of rotation is the same as in the southern hemisphere. The flow is geostrophic except in the porous section of the wall where the isobars are sharply bent, but the flow is normal to the wall.

to maintain a convergent viscous bottom layer to carry water from the rim to the center and to permit the surface to rise at the fixed rate $\dot{\zeta}$.

Radial Wall with a Small Porous Section. In Fig. 2 there is sketched the isobaric pattern which would ensue in this experiment when only a small portion of the wall is porous and the inner and outer portion solid. The angular rotation has been assumed to be negative (corresponding to the southern hemisphere), and attention is directed to the similarity of the pressure pattern in the Antarctic Circumpolar Current. The porous section of the wall, which is supposed to represent Drake Passage, is drawn on an enlarged scale (in angle, φ) to show detail of the pressure field through the wall.

In the outer region near the rim source S_1 , the flow is radially inward; pressure, in arbitrary units, is highest (12) on the coast corresponding to Chile and lower (10) on the coast of Argentina. The isobaric pattern in the zone where the wall is porous spirals inward, so that the geostrophic flow has a large eastward component. As one proceeds to smaller radius, the pressure rapidly falls. The flow in the porous wall itself is not geostrophic, the fluid here being able to drop down to lower pressure. The innermost zone is also geostrophic and is directed toward the central sink $-S_0$. The lowest pressure (5) is in the region corresponding to the Weddell Sea. The distributed sink over the entire surface, $\dot{\zeta}$, is thought to correspond to the divergent wind-driven Ekman layer actually present on the top of the Antarctic Ocean. I am reluctant to press the analogy further. The model is extremely artificial and particular, but it may stimulate some more physically plausible interpretation of the quite perplexing Antarctic Circumpolar Current.

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