Comments on ''On the Obscurantist Physics of 'Form Drag' in Theorizing about the Circumpolar Current''

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In a recent note, Warren et al. (1996 , WLR hereafter) presented the opinion that considerations of form drag in the dynamics of the Antarctic Circumpolar Current (ACC) are obscurantist in nature and a distraction from the more promising ''Sverdrup'' approach to ACC dynamics. I would argue that, on the contrary, the concept of form drag is one of several important considerations in understanding ACC dynamics and is the one that most clearly distinguishes the ACC from midocean gyres.

The fundamental difference between the ACC and the North Atlantic may be illustrated by the following thought experiment. Add an eastward wind stress with zero curl to the mean wind field forcing the flow, and see what happens. In the North Atlantic, for the vertically integrated flow, nothing need happen. The circulation pattern is determined by the wind stress curl, and the added irrotational stress makes no difference. There is a difference, however, in how the flow is distributed in the vertical. The added wind produces a southward flow in the surface Ekman layer and, to close the meridional circulation, this must return north lower down. This can be achieved by a large-scale tilt in the sea surface, inducing a northward geostrophic flow, together with an opposing tilt in isopycnals to cancel that flow below the thermocline.

Or, to put it another way, the added eastward force due to the wind stress is balanced by a tilt in sea surface that causes the ocean (above the thermocline) to push harder on the eastern boundary than on the west. This second way of describing things is possible because, for a closed zonal section across which there can be no mean mass flux, the net effect of the Coriolis force is zero. Coriolis is important for individual fluid elements though, so the integral balance between pressure gradient and wind stress can be reinterpreted in terms of the meridional circulation.

Now consider what would happen in a flat-bottomed Southern Ocean. A Sverdrup balance still determines the meridional component of the vertically integrated flow, and where there are eastern boundaries, the zonal component can also be calculated in the conventional manner. At latitudes with no boundary, however, an arbitrary function of latitude can be added to the Sverdrup solution. Sverdrup dynamics do not constrain the strength of the ACC, and the strength of the ''free mode'' must be determined by considering how the zonal wind stress is balanced. With no bottom topography, this must be a frictional (or eddy) mechanism, so the flow becomes strong enough for lateral or bottom friction to balance the wind stress. In terms of the meridional circulation, the northward flow in the Ekman layer is now balanced by southward flow either in the bottom Ekman layer or across the body of the current, in both cases balanced by friction. In this case, addition of an eastward wind stress with no curl makes a large difference to the flow, increasing the total transport of the ACC.

The enormous ACC transports that result from the frictional balance led Munk and Palmén (1951) to consider the Southern Ocean with bottom topography. There is still a free mode. Any eastward flow that is purely a function of latitude can be added without affecting a Sverdrup balance, as long as it does not penetrate deep enough to intersect with the bottom topography, so again the Sverdrup balance does not determine the transport of the ACC unless a value for this free mode is specified. The difference made by bottom topography is that it is now possible to balance the wind stress with a form stress, without resorting to frictional control and the large transports that implies. As WLR point out, this form stress is simply the result of a geostrophic southward return flow to close the meridional circulation, so it might be thought that this can be considered independently of the ACC transport. There are two reasons why it is not safe to assume this:

First, unlike the North Atlantic, this return flow is separated from the surface Ekman flow since it must occur below some sill depth in the Drake Passage latitudes. This implies that subduction and subsequent

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(presumably isopycnic) advection allows the meridional overturning to reach the sill depth. Döös and Webb (1994) have shown how, in the Fine Resolution Antarctic Model (FRAM), the meridional overturning occurs as small vertical excursions following isopycnals, adding together to give large vertical excursions in the zonal mean. No water particle moves down from surface to sill depth, instead the particles transfer potential angular momentum to lower particles by interfacial form drag (not in this case a ''hypothetical agency,'' but a modeled effect). Thus, the meridional circulation can be closed by zonal mean circulations in the Ekman layer and below the sill depth without requiring water particles to make the excursion between these depths. The mechanism by which this overturning is realized, though, requires an ACC that penetrates to below the sill depth. In this manner, the form drag contributes indirectly to the strength of the ACC.

Second, the way in which the return flow comes about may itself affect the strength of the ACC. If the return were simply below the sill depth in Drake Passage (about 3000 m) then it could form a western boundary current and there would be no problem, but this may not be what happens in practice. Döös and Webb (1994) showed that most of the return flow in FRAM occurs between about 2000- and 3500-m depth, and so cannot be supported by topography in Drake Passage. Webb (1994) showed that a simple model of the return flow in which it is supported against a series of overlapping partial meridional barriers requires a strong zonal flow in order for a single-valued pressure field to result (another way of looking at the balance between wind stress and form drag). See also Ishida (1994) for a related model. Realistic topography may alter the balance (and may also alleviate the necessity for deep western boundary layers), but it clearly cannot be taken for granted that the form drag balance can be achieved with no effect on ACC transport.

Finally, it is worth noting that the form drag balance and Sverdrup balance (when considered with bottom topography) are both examples of the integral constraints that can be derived from the vertically integrated momentum equations (see Hughes and Killworth 1995). Another of these is a form drag balance for wind stress integrated along streamlines of the vertically integrated flow. Physically, this is because the vertically integrated Coriolis force due to flow across streamlines must be zero. Since streamlines close in all ocean basins, perhaps this other form drag balance can also be a useful concept in considering the North Atlantic Circulation.

Several useful points are made by WLR. In particular, it is certainly true that an understanding of the equivalence between the form drag balance and closure of the meridional circulation are vital to a proper understanding of the physics of form drag. To then say that by virtue of this equivalence, form drag is irrelevant to the circulation or strength of the ACC is, however, clearly an overstatement.

REFERENCES

Döös, K., and D. J. Webb, 1994: The Deacon cell and other meridional cells of the Southern Ocean. *J. Phys. Oceanogr.,* **24,** 429–442.

Hughes, C. W., and P. D. Killworth, 1995: Effects of bottom topography in the large-scale circulation of the Southern Ocean. *J. Phys. Oceanogr.,* **25,** 2485–2497.

Ishida, A., 1994: Effects of partial meridional barriers on the Antarctic Circumpolar Current—Wind-driven barotropic model. *Dyn. Atmos. Oceans,* **20,** 315–341.

Munk, W. H., and E. Palmén, 1951: Note on the dynamics of the Antarctic Circumpolar Current. *Tellus,* **3,** 53–55.

Warren, B. A., J. H. LaCasce, and P. E. Robbins, 1996: On the obscurantist physics of ''form drag'' in theorizing about the Circumpolar Current. *J. Phys. Oceanogr.,* **26,** 2297–2301.

Webb, D. J., 1994: A simple model of the effect of the Kerguelan plateau on the strength of the Antarctic Circumpolar Current. *Geophys. Astrophys. Fluid Dyn.,* **70,** 57–84.