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We (Warren et al. 1996, hereafter WLR 96) observed that, if Ekman dynamics operates in the Southern Ocean to the same extent as is thought in the rest of the world ocean, then the mean eastward wind stress penetrates only into a thin surface layer and forces a mean northward transport across the Drake Passage zone in that layer. Since there is no significant outflow from Antarctica, this transport must be supplied by upwelling between the zone and the continent. That, in turn, is necessarily fed by deep southward flow below the crests of the ridges that span the Drake Passage zone. This can be a geostrophic flow, with the ridges supporting the net zonal pressure difference(s) required. Thus, the lowest-order, vertically and circumpolarly integrated zonal momentum balance in the Drake Passage zone is between the eastward wind stress, representing the northward Ekman transport, and the net cross-ridge pressure difference, representing the southward geostrophic flow. The Circumpolar Current does not appear in this balance, but it is no more surprising to find the zonal momentum equation describing the meridional, rather than the zonal, flow here than it is to use the zonal pressure gradient to calculate the northward transport of the Gulf Stream in the Straits of Florida.

Olbers, in his introductory remarks and his section 2, appears to accept all this. Yet at the same time he disputes two basic features of the physics: (a) While the cross-ridge pressure difference is set up to close the

meridional circulation driven by the Ekman transport, Olbers wants it (also? instead?) to be a “bottom form drag” emanating from, or acting on, the Circumpolar Current. (b) Although the wind stress is entirely absorbed in a surface boundary layer, Olbers wants still to transmit it by “interfacial form stress” to the bottom, in order to balance the “bottom form drag” (notwithstanding that this cross-ridge pressure difference is already balanced by the Coriolis acceleration associated with the deep southward flow and is thus linked to the wind stress by the meridional circulation).

With regard to (a), Olbers simply asserts without proof in his introductory section that “a flow in response to passing over topographic features must set up a pressure field which correlates with the topographic elevation to produce a bottom form stress.” Then, in his section 3, he calls up a barotropic model that Charney and De Vore (1979) had constructed to illustrate a simple mechanism for atmospheric blocking. He derives from it a velocity-dependent formula for form stress, with which to calculate zonal transport. As applied to the Circumpolar Current, the result is evidently unrealistically large, even to order of magnitude. He goes on to say, however, that a two-layer version of the model (Olbers and Völker 1996) produces reasonable values; but, as we understand that model, these values are for an unstable state, from which the system relaxes to a frictionally dominated one, with very large transports again. Both models are founded on a zonal flow confined by channel walls and thus forced to pass over sinusoidal topography; both use severely truncated Fourier representations. While one cherishes models that are simple enough to be understood, we doubt whether the balances struck in these are even qualitatively relevant to the Circumpolar Current, given the vastly different geometry and physics of the actual system.

In sections 4–6, Olbers develops his concepts of “in-

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terfacial form stress.” In his section 4 he considers the zonal pressure gradient in a layer of varying thickness and depth. Integrating it zonally by parts, he obtains terms depending on the slopes of the upper and lower surfaces, and he defines them as “form stresses.” He seems to regard these surfaces as “material surfaces,” although the structure of his argument does not require them to be such, and, in fact, it would allow them to be anything—surfaces of constant sound velocity or silica concentration, say, or freely drawn surfaces unrelated to water properties at all. This notion of interfacial form stress is thus a mathematical construction rather than a physical concept, derived not from a downward flux of momentum but from an arbitrarily varying vertical interval over which one chooses to integrate the zonal pressure gradient. For example, defining a layer so that it is thick where the zonal pressure gradient is positive, say, and thin where the gradient is negative can generate a net positive value for the circumpolar integral, but not because any physical process is transferring momentum vertically into the layer. To call the variable-limit terms that measure this net positive value “form stresses” seems obfuscatory.

In sections 5 and 6 Olbers uses conservation equations for mass and temperature, (10) and (11), to construct a divergence of an “interlevel form stress.” These equations, however, are just bookkeeping statements—what goes in (mass, energy) must equal what goes out—and they do not, in themselves, embody mechanisms for driving motion. To manipulate them so as to obtain an expression for the meridional mass flux (16) in terms of the net heat flux involved in the budgeting balance, and then to multiply that by f (18), does not identify a new kind of stress, or discover a new driving mechanism. It simply generates an alternative (and more complicated) way of writing the Coriolis acceleration associated with the meridional motion driven by the external forcing. It is therefore not surprising that the conclusion of this endeavor [Eq. (24)] is just a restatement of the fact that net northward Ekman transport is compensated by southward geostrophic flow, except that now the cross-ridge pressure difference that supports the geostrophic flow is labeled “bottom form stress.” That some numerical models exhibit this balance gives one confidence in the models, but in no way validates the associations that Olbers attaches to his term “bottom form stress.” Nothing seems to have been developed here about the dynamics of the Circumpolar Current.

That the balance between wind stress and cross-ridge pressure difference describes a meridional circulation, and is irrelevant to the Circumpolar Current, was, and remains, our main point. We (WLR 96; Warren et al. 1997, hereafter WLR 97) then went on to revive the suggestion (Stommel 1957) that Sverdrup-transport theory offers a more promising account of the current field (as elsewhere in the world ocean). We restated that the Circumpolar Current is far from being a zonal, channel-like flow: that it spirals southward from the western

Atlantic to the eastern Pacific, that the full meridional span of the spiraling current is six times that of Drake Passage, and that the circulation is completed by a northward western-boundary current, the Falkland Current, along the east coast of South America. Present-day agreement between calculations of the southward Sverdrup transport across latitudes 55°–60°S and the measured transport of the current in Drake Passage (upstream end of the western-boundary current) is excellent.

Nevertheless, Olbers (section 7) objects, in part because we disregarded the contribution of bottom vertical velocity (due to flow up or down sloping topography) to the vertically integrated vorticity equation. In fact, we did recognize that in a few places the current appears guided by bottom topography, and so experiences upslope and downslope motions. But we considered that these localized positive and negative vertical velocities would cancel out in areal average, and that, in that regional sense, Sverdrup balance should be valid. Olbers, however, seems to believe that the current reaches, and feels, the bottom everywhere and that one cannot disregard the bottom component of the vortex-stretching term.

Some review of the limited evidence for the depth of the Circumpolar Current may therefore be pertinent here. The outstanding instance of correlation between current path and bottom topography is found in the western Pacific sector of the Southern Ocean, where surface dynamic height contours are concentrated along the Pacific–Antarctic Ridge, and then turned sharply southeastward above the Udintsev Fracture Zone; perturbations to the current path above the Kerguelen Plateau (Indian sector) and eastern Southeast Indian Ridge (south of the Tasman Sea) are also quite marked (Gordon et al. 1978). These ridges are high features, reaching to within less than 2500 m of the sea surface. Drake Passage is somewhat deeper, sill depth more like 3500 m. Four cross-passage geostrophic velocity sections referenced to direct current measurements show the characteristic bandedness of the Circumpolar Current at all depths, but with roughly equal eastward and westward flows at the bottom, so that the cross-passage mean throughflow velocity near 3500–4000 m is probably not statistically significantly different from zero (Nowlin et al. 1977; Whitworth et al. 1982). Moreover, the mean geostrophic transport above and relative to 3000 m in Drake Passage is $103 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Whitworth et al. 1982), close enough to the directly measured transport of $130 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ for the full passage section to indicate slight mean bottom flow at most there. Where the current flows above the broad and much deeper basins of the Southern Ocean (e.g., Bellingshausen Basin), it certainly does not reach to the bottom because the upper-level dynamic-height contours are not at all congruent with the isotherms of bottom potential temperature (Gordon et al. 1982).

It thus seems likely that the current extends down

only to depths of 3–4 km or so, that only rather high ridges can therefore force vertical velocities at its base, and that our assumption of negligible deep vertical velocity on regional average is probably valid. Models, on the other hand, may be exaggerating the vertical extent of the Circumpolar Current, and thereby the bottom vertical velocity as well. The FRAM, for example, overestimates the transport of the current in Drake Passage by 50%, which error is probably associated with unduly large bottom velocities there (Webb et al. 1991).

Olbers goes on to try to uncover “form drag” in the Sverdrup relation itself, but the term he so identifies in his Eq. (26) is just the geostrophic approximation to the bottom limit of the vertically integrated vortex-stretching term (occasionally called “bottom torque”—surely one of the more inept bits of verbiage in the literature, given that the term has neither the form nor the dimensions of torque). In (26) the cross-ridge pressure differences are said to be due to hypothesized *net* upslope or downslope flow by a bottom-reaching Circumpolar Current, whereas in (6) they balanced the deep southward geostrophic flow beneath or through the Circumpolar Current that supplied the northward Ekman transport. Readers will have to judge for themselves whether it is helpful to label such vortex-stretching “form drag,” and whether the net upslope and downslope flow of the Circumpolar Current around Antarctica ought to be non-zero. In any case, (26) is of very limited interest because it is derived from (25) on the assumption that stress curl and vortex stretching alone are sufficient to guarantee zero net meridional mass flux (5). That is no more to be expected for a circumpolar section than for a transatlantic one: in both cases, Sverdrup dynamics has to be supplemented with additional physics to generate the western-boundary currents that satisfy continuity. Indeed, the Falkland Current is a prominent component of the Circumpolar Current system, still flowing northward at a directly measured rate of $60 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in the upper 3000 m at latitude 42°S (Peterson et al. 1996), even after discharging much of its transport into the western South Atlantic in latitudes 45° – 55°S (Gordon et al. 1978).

In section 8 Olbers retreats from even this approach to Sverdrup-transport theory, and attempts to recover a dependence of Circumpolar Current transport on the wind stress itself rather than its curl. He does so by reintroducing bottom friction (that he had acknowledged in section 2 to be negligible), representing it as proportional to the current transport. We (WLR 96, 97) already remarked that with a level bottom the northward surface Ekman transport would have to be supplied by southward flow in a bottom Ekman layer, whose existence would demand an eastward current of rather large magnitude. But with meridional ridges to support a southward *geostrophic* flow instead, the connection between wind stress (rather than its curl) and Circumpolar Current transport vanishes. Of course, it has also been recognized at least since Gill (1968) that the Circum-

polar Current is much too weak to generate a bottom stress comparable to the surface stress, so friction does not, effectively, couple the transport to the wind stress itself. In this respect Olbers’s proposal is retrogressive. On the whole, it seems odd to us to want to reject the successes of Sverdrup-transport theory in accounting for both the overall path of the Circumpolar Current (Baker 1982; Godfrey 1989; Chelton et al. 1990) and its transport through Drake Passage (e.g., WLR 96).

We are not sure, but we suspect that some of the historical desire for a “form drag” force comes from an intuitive feeling that, in the absence of meridional boundaries, a steady eastward wind stress would accelerate an eastward current indefinitely if there were no other force to stop it. This is true for an inertial frame of reference, but a steady zonal wind in a rotating system drives steady net meridional flow in a surface boundary layer instead, where the stress divergence is balanced by the Coriolis acceleration associated with the meridional flow, so the existence (or not) of meridional boundaries is irrelevant to this specific point. Hence, the cross-ridge pressure differences do not act to retard the Circumpolar Current (they are not a “form drag” force), but to support the geostrophic flow that feeds the surface Ekman transport.

In a more general context, C. Wunsch pointed out to one of us many years ago that a steady wind in a rotating system is a rotating wind in an inertial frame, so over the course of a rotation period the stress vector imparts no net momentum to the ocean. Moreover, the momentum equation for the frictional velocity components in the ocean, again as viewed from the inertial frame, is just the heat equation with a periodic upper boundary condition (the oscillating stress components)—which makes it perfectly obvious why the wind stress penetrates only into a thin surface layer.

Olbers informally pointed out that we misplaced the ρ and bungled a sign in our (WLR 96) Eq. (1). These slips had no bearing on our argument, but they are embarrassing, so we want to correct them.

Some of Olbers’s quotations from WLR 96 are inexact. If one cares about details, he should refer to our paper.

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