In our note we pointed out that if Ekman dynamics pertains to the Southern Ocean as much as is thought to the rest of the global ocean, then the eastward wind stress acting on the ocean is absorbed in a thin surface layer, and there is no stress below this Ekman layer to be transmitted to greater depths. In the zonal momentum equation the imposed wind stress is balanced by the Coriolis acceleration of the resulting northward Ekman transport. This transport is fed by deep upwelling, which must in turn be supplied by southward flow at depth. As we remarked, and as Hughes restates, if the ocean floor were level in the continentally unbounded zone of Drake Passage, this flow would necessarily occur in a bottom Ekman layer, and a powerful zonal current would be required to establish that layer.

However, long ridges cross the Drake Passage zone, so the southward flow can be geostrophic, with the cross-stream pressure gradient(s) supported by cross-ridge pressure differences. In this case the linkage between meridional circulation and zonal flow is broken, so the zonally integrated momentum balance cannot be used to deduce the zonal velocity at zonally unblocked levels, as in the flat-bottom case (Gill 1968). As we emphasized, this balance can be achieved with zero zonal flow when the southward motion is geostrophic. For this reason we think it is obscurantist physics to name these cross-ridge pressure differences “form drag” and to suppose it to be a force that brakes the Antarctic Circumpolar Current against an accelerating wind stress. This was (and is) our main point. (We did not say that “form stress is simply the result of a geostrophic southward return flow”: rather, that the notion of “form stress” is a misunderstanding and mislabeling of the pressure difference associated with the flow.) There are not, as Hughes seems to imply, two parallel, equivalent ways of interpreting the same algebra here, because the zonal current and a stress throughout the water column are central to form-drag constructions, whereas in fact, both the zonal current and any stress below the Ekman layer are irrelevant to the actual physical relation between wind stress and cross-ridge pressure difference.

Hughes doubts this complete irrelevance, and in support perhaps of some indirect (but unspecified) influence of cross-ridge pressure differences on the Circumpolar Current, he cites two results from the FRAM that appear to contradict the simple meridional circulation outlined. Following Döös and Webb (1994), he states that in the downward limb of the meridional circulation in the FRAM “no water particle moves down from surface to sill depth” but that a series of particles each moves a short distance in a vertical sequence, each transferring its momentum to the next one below. This would be a disturbing situation in the ocean, because in the upward limb of the meridional circulation there particles certainly rise from great depth to the surface layer: to close their trajectories they must all then return to great depth—somewhere (perhaps the subpolar North Atlantic).

Hughes also states that in the FRAM, the southward flow across the Drake Passage zone occurred at depths of 2000–3500 m [2400–4100 m, according to Saunders and Thompson (1993, Fig. 2)], whereas the sill depth of Drake Passage is about 3000 m. However, the Drake Passage zone is blocked more critically in the Atlantic by the South Sandwich Islands ridge, whose effective sill depth (disregarding a few very narrow passages) is more like 2000 m. (The Circumpolar Current avoids this ridge by slipping northward through a gap in the North Scotia Ridge.) We are not sure where, or at what depths, the North Atlantic Deep Water crosses the Drake Passage zone to become the Warm Deep Water found farther south. Probably it is entrained in the local circulation and makes one or two circuits around Antarctica before completing a spiral crossing of the Circumpolar Current. Some such long time interval is indicated...
because the North Atlantic Deep Water is oxygen-maximum water in the western South Atlantic, but the metamorphosed Warm Deep Water is oxygen-minimum water (Gordon et al. 1982).

In their own analysis of the FRAM, Saunders and Thompson (1993) succinctly expressed the dynamical issue: “If momentum balance is essentially assured by mass conservation, one must appeal to the vorticity balance to understand the strength of the ACC.” (By “mass conservation” they meant the meridional circulation composed of northward surface Ekman transport and compensating deep southward geostrophic flow.)

Therefore, following our main point, we reviewed the impressive success of Sverdrup dynamics in accounting for both the circulation pattern of the Antarctic Circumpolar Current and its volume transport. The Southern Ocean is problematical for Sverdrup dynamics, however, because, as Hughes emphasizes, the continentally unbounded Drake Passage zone provides no “eastern boundary” at which the zonal velocity component can be prescribed as zero, but instead offers the possibility of an undetermined zonal current as a “free mode” in the system. We think that Hughes exaggerates the difficulty posed by this ambiguity. One would not expect to find a truly free mode (i.e., unforced zonal flow) in the mean, or steady, ocean circulation anyway, because, if one were initiated, friction would destroy it. This expectation is consistent with observations. The unblocked Drake Passage zone occupies lat 57°–62°S (southern tip of the South American continental shelf to South Shetland Islands off Antarctic Peninsula). In the eastern South Atlantic and south of Africa the Circumpolar Current lies entirely to the north of this zone, and even as far east as Australia, nearly all of the current still lies north of 57°S (Gordon et al. 1978). There is thus no circumpolar zonal current in the Drake Passage zone, no free mode that needs special dynamics to account for it.

Given the great breadth of the zone in which the Circumpolar Current flows, 40°–70°S (e.g., Gordon et al. 1978), it seems to us that South America and the Antarctic Peninsula really do provide a fairly effective eastern boundary, penetrated only by a relatively small gap. Without the gap the Sverdrup circulation forced by the negative wind-stress curl over the Southern Ocean would form a closed gyre, with a western-boundary current flowing northward along the Antarctic Peninsula and South America to absorb the westward interior flow south of the wind-stress curl minimum, and to provide the eastward interior flow north of it. With the gap open, however, that gyre cannot close, so the interior flow forced in lower latitudes (Circumpolar Current) simply passes through the gap to supply the South American western boundary current. The rate of throughflow (Baker 1982) is given by the circumpolar integral of the wind-stress curl along a latitude near the northern edge of the gap (almost exactly as observed), just as the transport of the Florida Current is specified by the transatlantic integral of the wind-stress curl (e.g., Leetmaa et al. 1977). And the Sverdrup transport forced south of the gap forms closed gyres in the Weddell–Enderby Basin and Ross Sea (e.g., Deacon 1979; Gordon et al. 1981), with the Antarctic Peninsula as principal western boundary. Veronis (1973) developed a model of the Circumpolar Current along somewhat similar lines. Needless to say, channel models of the current are remote from this schematic.

REFERENCES