The Overturning Stream Function and the Deacon Cell

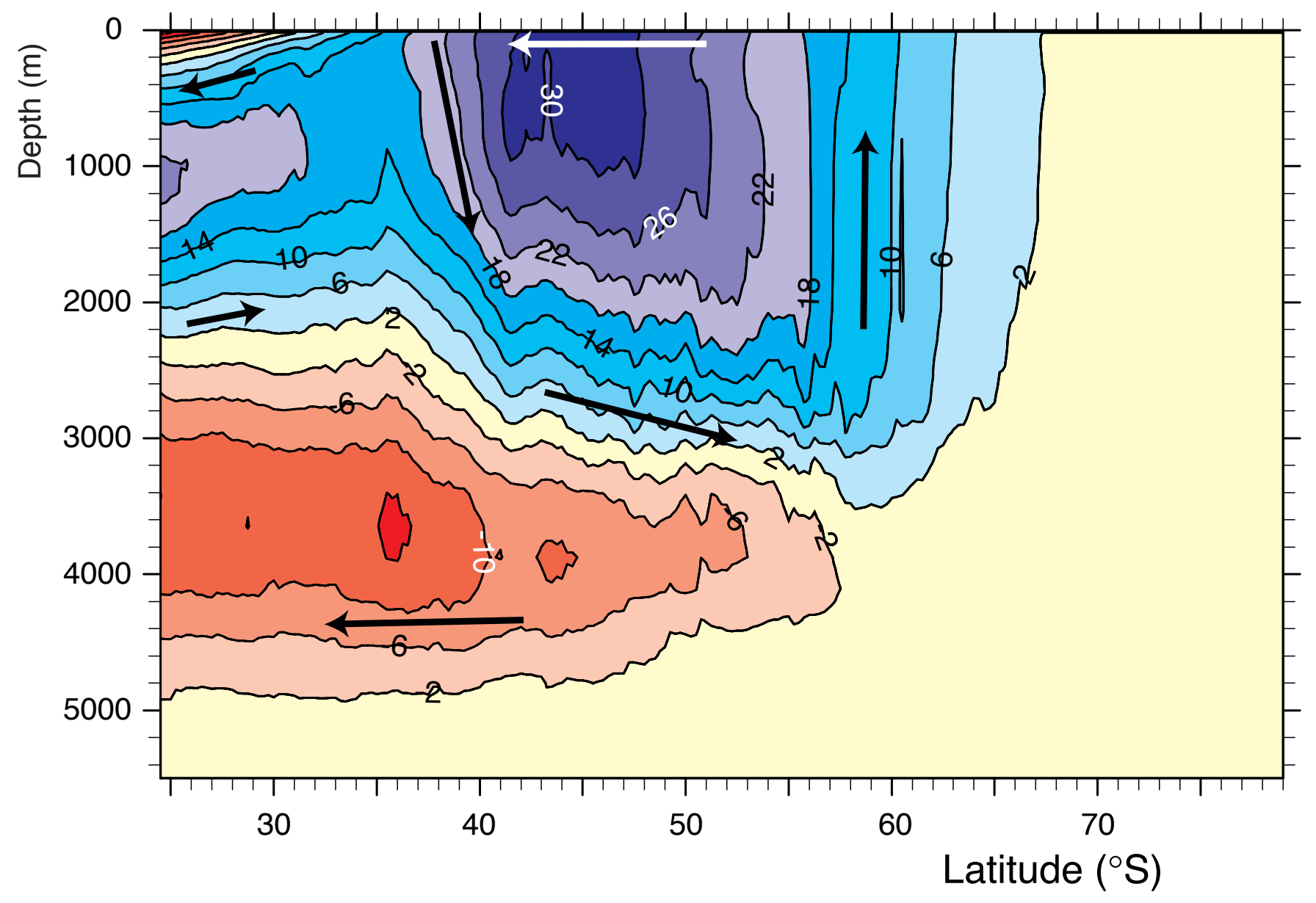

Figure 1. The overturning stream function as a function of latitude and depth

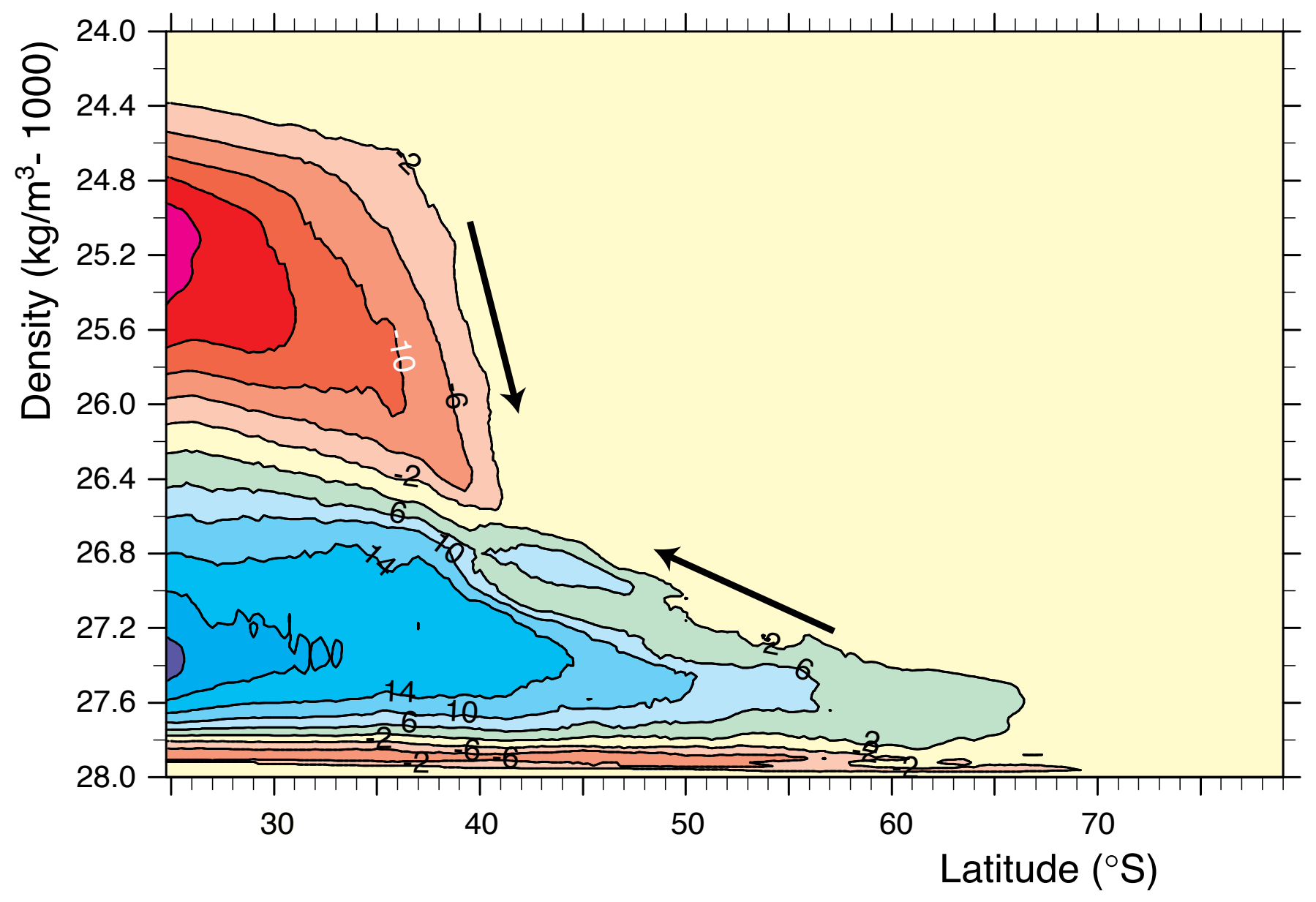

Figure 2. The overturning stream function as a function of latitude and density

The overturning stream function on depth levels is calculated by integrating the total north-south transport across a given latitude between the ocean bottom and individual depths. The FRAM overturning stream function is similar to that found with earlier low resolution ocean and climate models.

At depth, approximately 10 Sv of dense Antarctic Bottom Water, formed near Antarctica, flows north between 4000 and 5000m. At the surface the wind drives a northward Ekman transport that reaches 30 Sv near 45°S. The Ekman transport changes sign at 30°S and the resulting convergence and downwelling forms intermediate waters which sink away to the north at shallow depths.

At mid-depths, North Atlantic Deep Water (NADW) and other waters with similar density, move south between 1000 and 3500 m. They appear to sink near 45°S and then rise almost vertically in the top 2000 m at the latitudes of Drake Passage.

The odd feature of this figure is seen near 40°S. In a region only 5° wide over 12 Sv appears to sink almost vertically from the surface to a depth of 2000m. The closed cell formed by this 'sinking' flow is called the Deacon Cell.

Calculated on density surfaces, the overturning stream function shows significant differences. At depth Antarctic Bottom Water with densities near 27.9 still flows to the north. In the surface layers there is still a strong northward transport south of 40°S and similar southward flow near 30°S.

The first unusual feature is around 50°S, where the surface (Ekman) layer increases in buoyancy - at latitudes where the ocean is losing heat into the atmosphere. Almost the opposite is seen between 30°S and 40°S where the surface layers lose a significant amount of buoyancy. At 40°S some of this loss is used to reduce the buoyancy of water with densities near 26.5 and further south there is a continuing reduction in the intermediate water density.

At mid depths, over 16 Sv of NADW and other waters with densities near 27.8, flow south at 30°S. This flow reaches the surface affected layer south of 45°. Near Antarctica some of this replaces the bottom water flowing south. The rest flows north and eventually helps form intermediate water.

But the most important feature is that the Deacon Cell has all but disappeared. Except for a small feature near 45°S, 26.8 kg/m^3, there is nothing to be seen.

An Explanation of the Deacon Cell

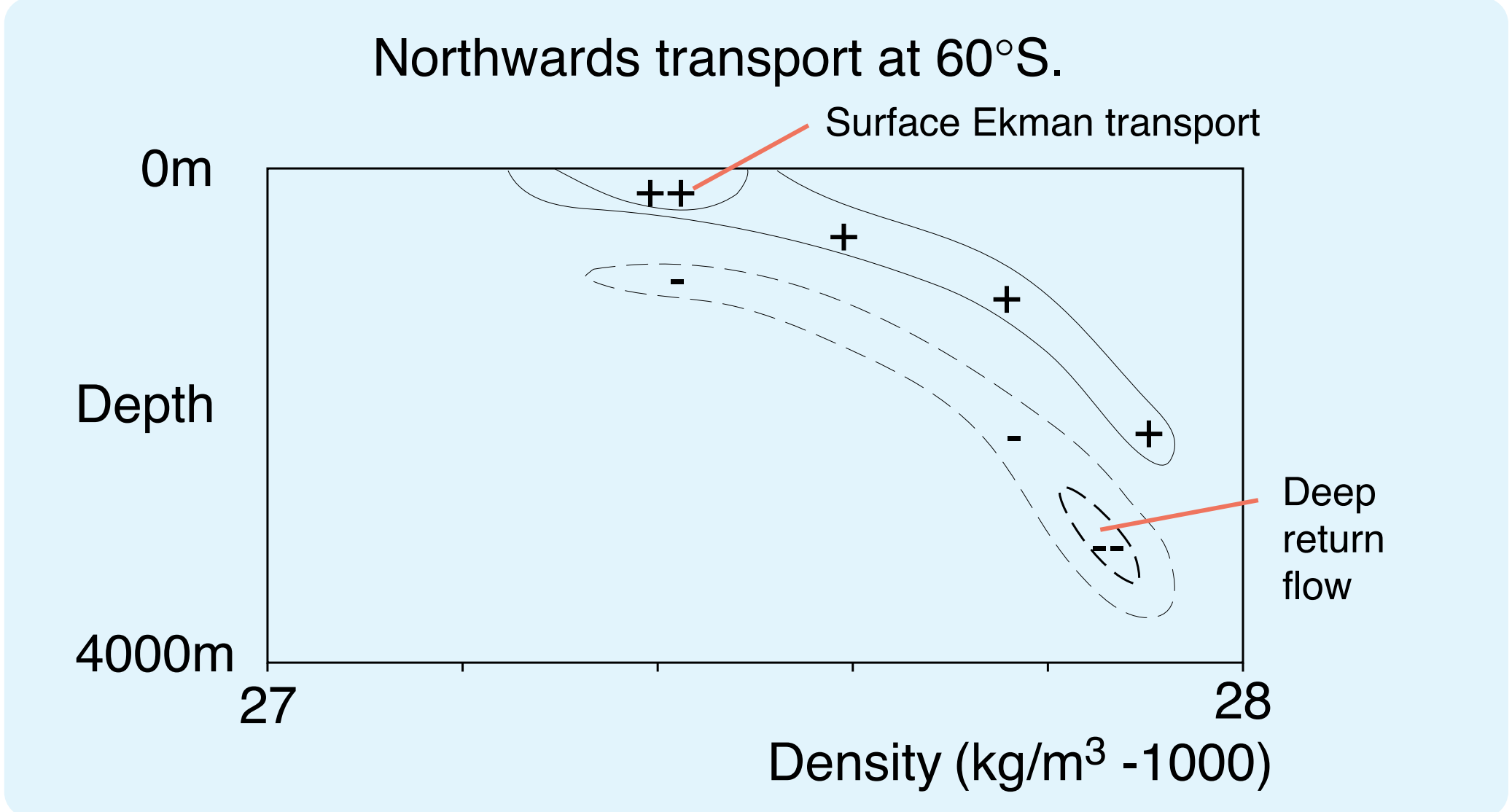

Figure 3. The northwards transport at 60°S as a function of density and depth (schematic)

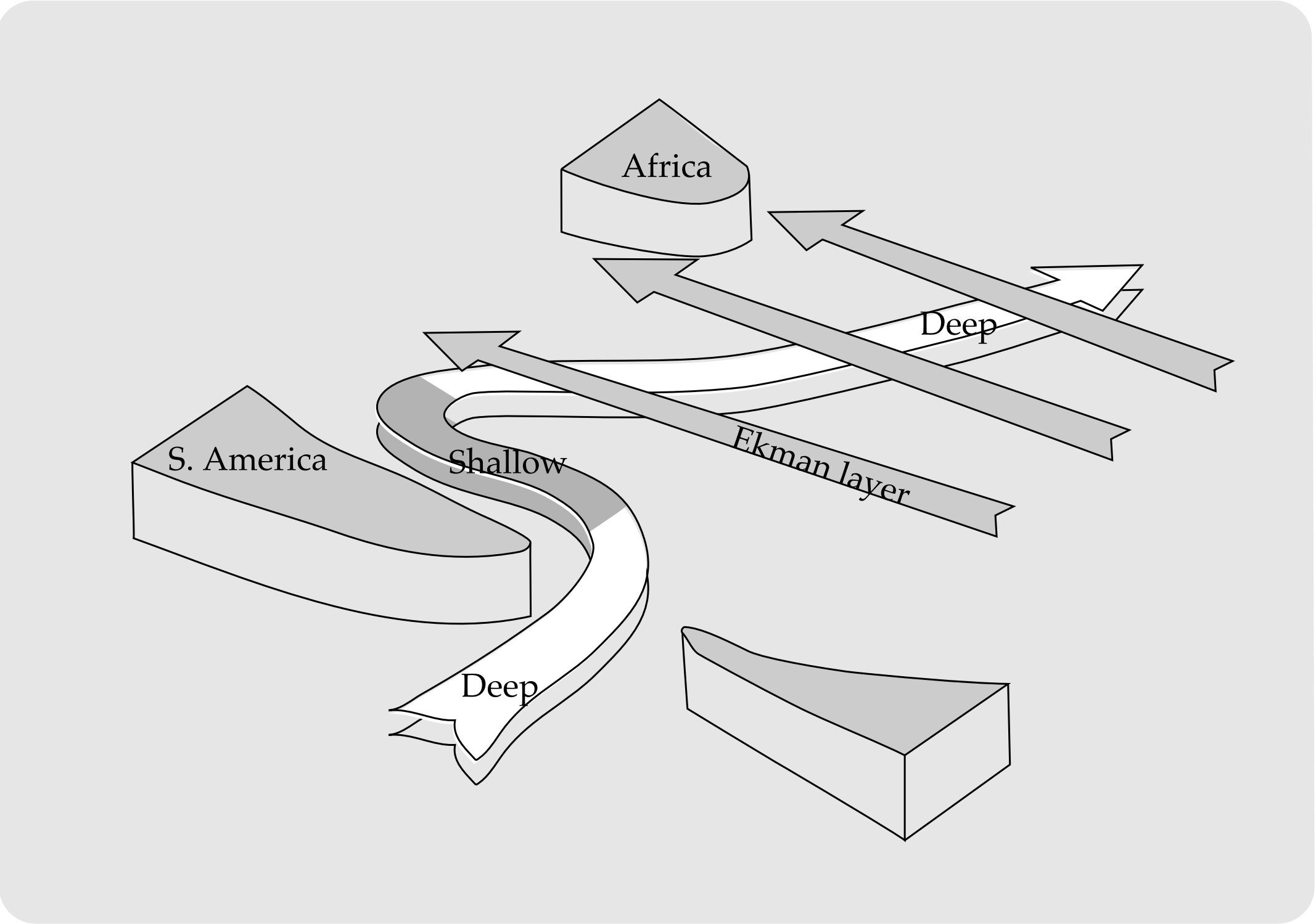

Figure 4. The large scale meanders of the ACC

To understand the structure of the Deacon Cell it is useful to plot the north-south transport as a function of both depth and density. The relationships are clearest at the latitudes of Drake Passage (i.e. 60°S) but the general picture is true at other latitudes.

Plots show that much of the northward transport in the surface layers flows back southwards at depths of 400 to 800 m. At these depths it is balanced by an equal and opposite flow of water masses of greater density, so there is no net Coriolis force due to the north-south flow. In angular momentum terms, the angular momentum lost by the southward flowing light water is exactly balanced by an angular momentum gain of the dense water mass flowing north.

This dense water returns at greater depth where it joins the southward flow of NADW and other water masses with densities near 27.8. At these depths there is no compensating flow of denser water because angular momentum can be lost by form drag, the torque acting on the solid Earth.

The results thus show that the Deacon Cell is in part an artifact resulting from calculating an average on depth surfaces instead of density surfaces. However it is also closely connected with the organized downward transfer of angular momentum from the ocean surface to the level of topography through a depth range in which there is no topography to support a net east-west pressure gradient.

Further investigation showed that, except for the Ekman layer, the northward transports occurred primarily in the longitude band between South America and the Mid-Atlantic Ridge. The main Deacon Cell is thus seen to be connected with a very large scale corkscrew motion of the water masses in the Antarctic Circumpolar Current.

In terms of eddy fluxes, this corkscrew motion is transferring the surface stresses downwards, not by fluctuations in the mesoscale eddy field, but through the large scale meanders or standing eddies of the Southern Ocean.

(Döös and Webb, JPO, 24, 429-442)

A Simple Model of the Antarctic Circumpolar Current

The studies with the FRAM model emphasized the point that the Southern Ocean is not a simple east-west channel. Any east-west line through Drake Passage encounters both the shallow topography of the Scotia Arc and the massive sunken continental block of Kerguelen. In the weakly stratified waters of the Southern Ocean the latter is particularly important, its stratified Taylor Column easily reaching the ocean surface.

The FRAM studies also emphasized the weakness of earlier theories for the strength of the Antarctic Circumpolar Current (ACC). A large part of the transport seems likely to be due to the westerly winds, but these drive the Ekman layer to the north and it is not obvious how this drives the ACC. However as FRAM showed the Ekman return flow was connected to the topography spanning Drake Passage. Maybe, together with Kerguelen, this is a clue ...

Assume that the Ekman return flow starts as a western boundary current off S. America, turns eastward to become a western boundary current of Kerguelen until it reaches the latitude where it upwells. It seems reasonable except that because of the presence of Drake Passage, if the rest of the ocean is still, then the pressures on either side of the eastward flowing jet must be the same. This is impossible as because of geostrophy, the current must then be zero (Fig 5a).

However if we add an ACC, which changes latitude in order to pass through Drake Passage and north of Kerguelen (Fig 5b), things are different. Because the latitudes of the two east-west jets differ, the transports associated with a given north-south pressure difference also differ and this difference can carry the Ekman return flow. Thus let f_n and f_s be the values of the Coriolis term affecting the two jets, let T_n and T_s be their transports and T_e (=T_n-T_s) be the Ekman return flow. Then

$$F_n T_n = F_s T_s, \quad \text{or} \quad T_s = T_e F_n/(Fs-F_n)$$

If the east-west jets are at 45°S and 58°S and if T_e is 25 Sv then the predicted transport of the ACC is 150 Sv.

Seen a similar theory before? The northern and southern branches of a Sverdrup gyre are also at different latitudes and also have the same pressure differences across them. The resulting difference in transport is just enough to supply the Ekman upwelling or downwelling in the eastern parts of the gyre with a north-south component to the flow.

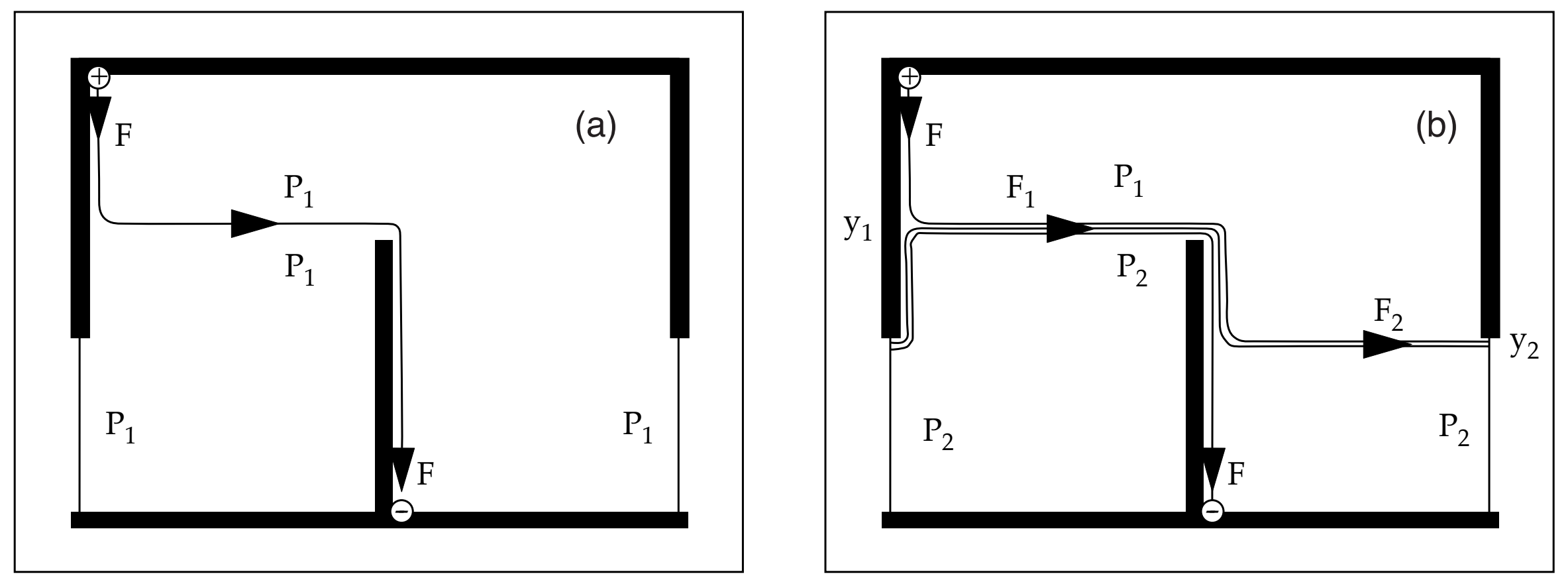

Figure 5. (a) If a Coriolis force is present a zonal channel with overlapping barriers cannot support a cross-channel source-sink flow. (b) If a zonal current is added, the cross channel flow is possible.

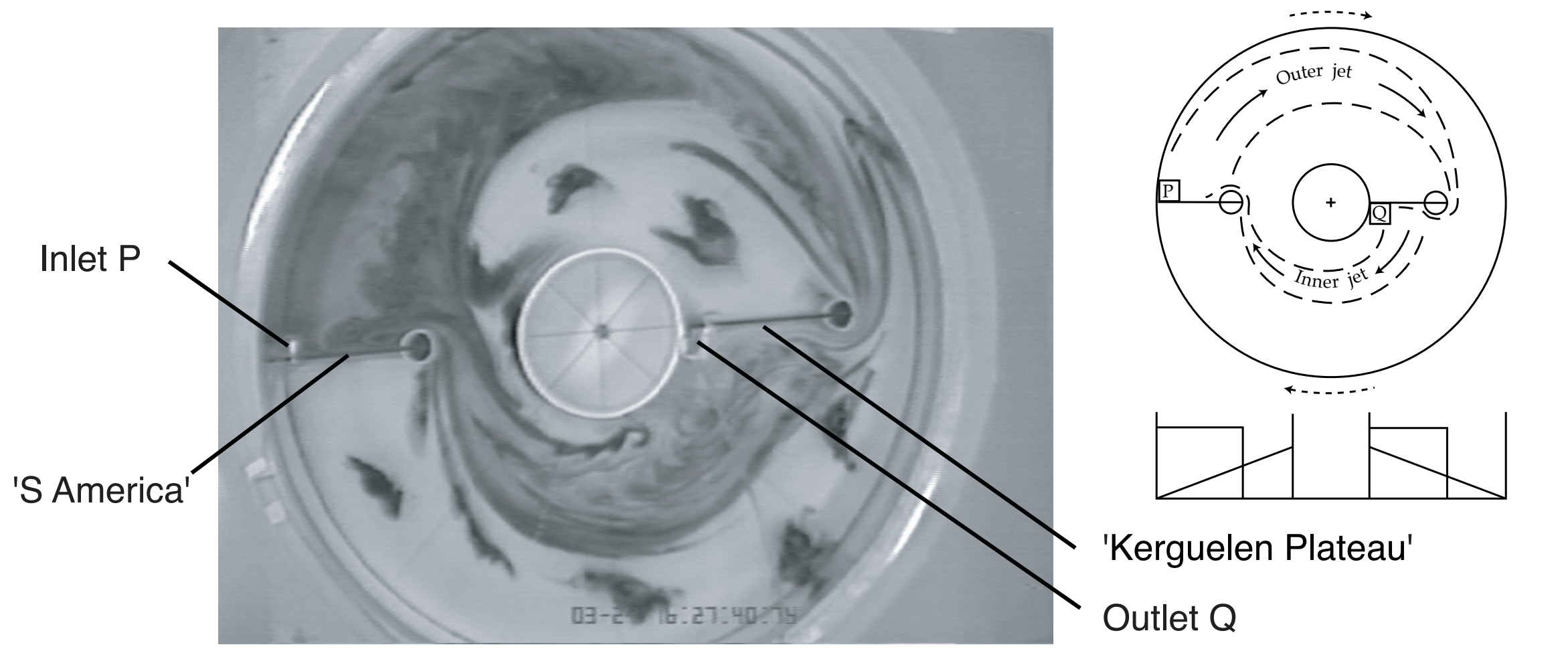

Figure 6. Rotating tank experiment with barriers representing S America and the Kerguelen Plateau. A radially sloping bottom reproduces the effect of changing f. Inflow at 'P' and outflow at 'Q' drives two 'zonal' jets around the tank, the tank's equivalent of the Antarctic Circumpolar Current.

A New View of the Thermohaline Circulation

Before FRAM the conventional view of the Thermohaline Circulation was one of deep convection at high latitudes with slow upwelling throughout the rest of the ocean. The main sites for deep convection were in the high North Atlantic and around Antarctica. In the North Atlantic the Norwegian and Labrador Seas were the source of North Atlantic Deep Water (NADW). Around Antarctica the Weddel Sea was one of the main sources of Antarctic Bottom Water.

The water travelled away from the convection regions until it reached the Antarctic Circumpolar Current, by which it was carried into each of the major basins of the world. After upwelling two main return paths were envisaged for NADW. The first, the warm path, extends from the N Pacific through Indonesia into the Indian Ocean and then, via the Agulhas Current, into the Atlantic. The second, the cold path, took a more direct path from the Pacific, through Drake Passage, into the Atlantic.

A revised flow pattern arose from the work with FRAM reported here, similar studies of the OCCAM model and parallel work by Toggweiler at GFDL. This revised picture takes into account the significant upwelling of NADW that occurs in the Southern Ocean.

Deep convection of NADW occurs as before in the North Atlantic. It spreads into the Southern Ocean where a large fraction is upwelled by Ekman suction. This water is driven north in the surface Ekman layer, where its density is reduced primarily by surface freshening. It then mixes with warm, salty water from the sub-tropical gyres and sinks below the gyres as intermediate water, eventually to upwell near the equator into the surface layers of the sub-tropics. Finally the flow returns to the North Atlantic as before.

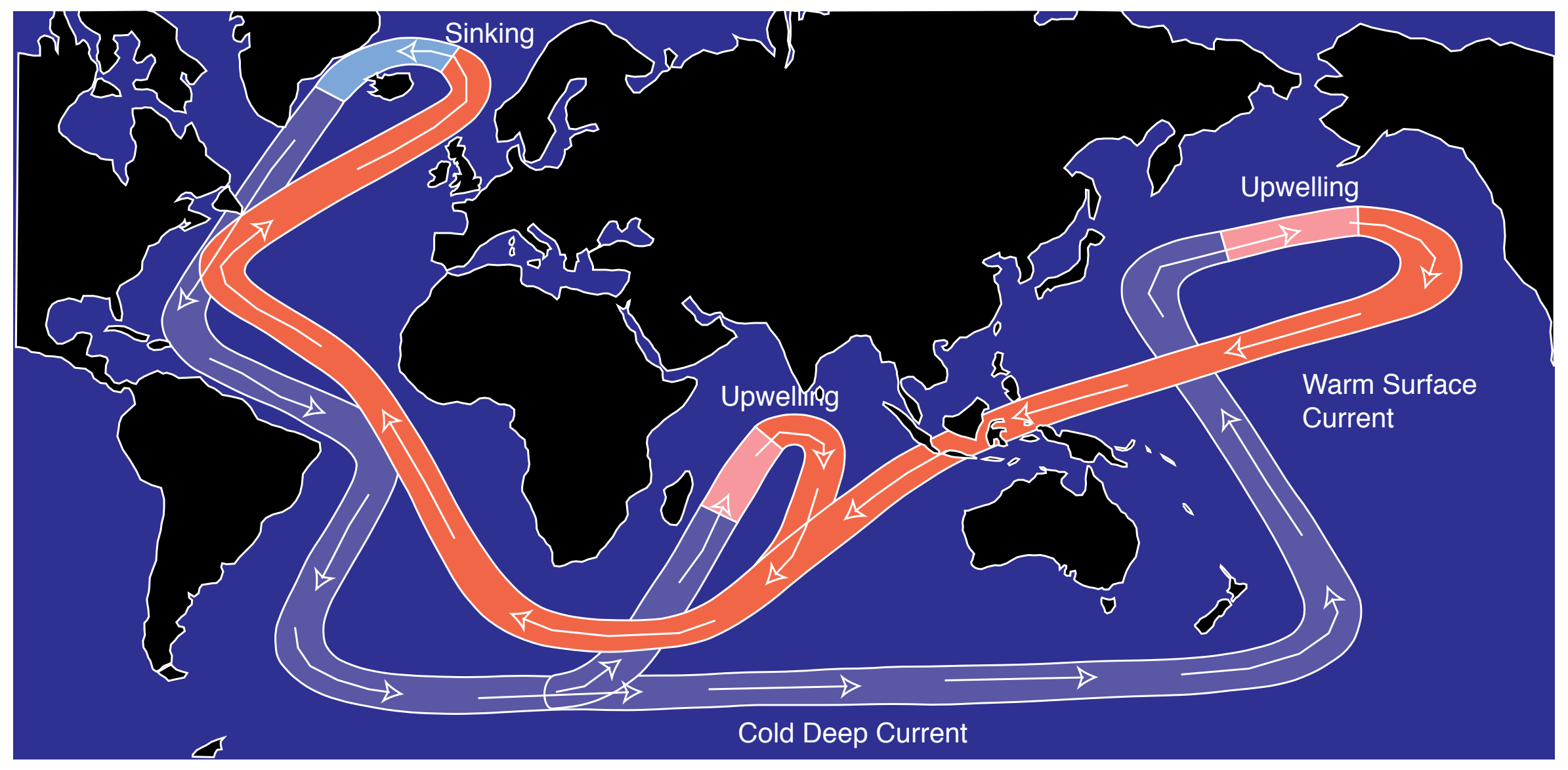

Figure 7. The traditional view of the Thermohaline Circulation

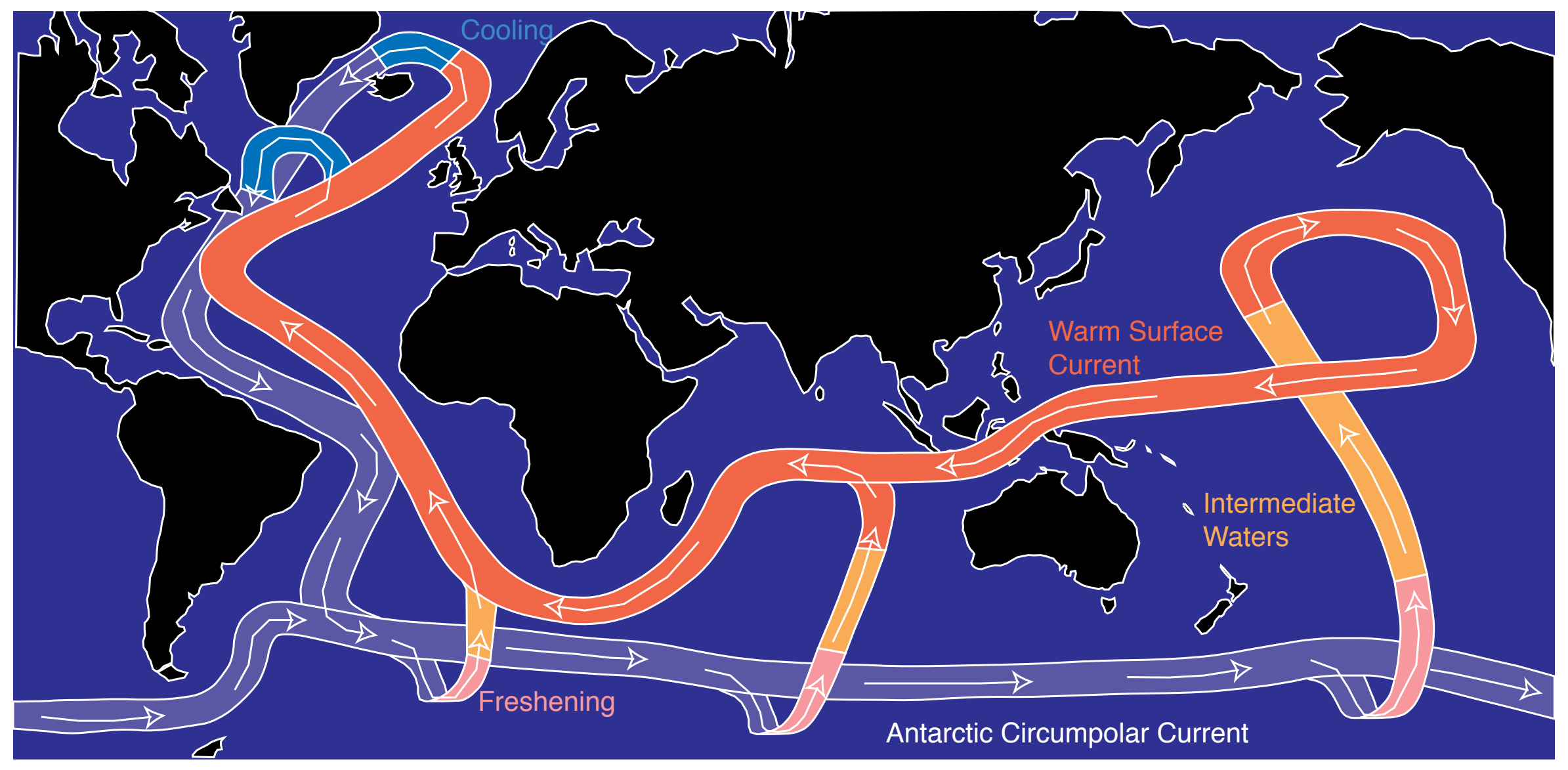

Figure 8. Southern Ocean Upwelling and the Thermohaline Circulation