Chapter 6

Antarctic oceanography

The region of the world ocean bordering on Antarctica is unique in many respects. First of all, it is the only region where the flow of water can continue all around the globe nearly unhindered and the circulation therefore comes closest to the situation in the atmosphere. Secondly, the permanent thermocline (the interface $z = H(x,y)$ of Figure 3.1) reaches the surface in the Subtropical Convergence (Figure 5.5) and does not extend into the polar regions; temperature differences between the sea surface and the ocean floor close to the continent are below 1°C and generally do not exceed 5°C, *i.e.* 20% of the difference found in the tropics (Figure 6.1). What this means is that our $1^1/_2$ layer ocean model cannot be applied to the seas around Antarctica.

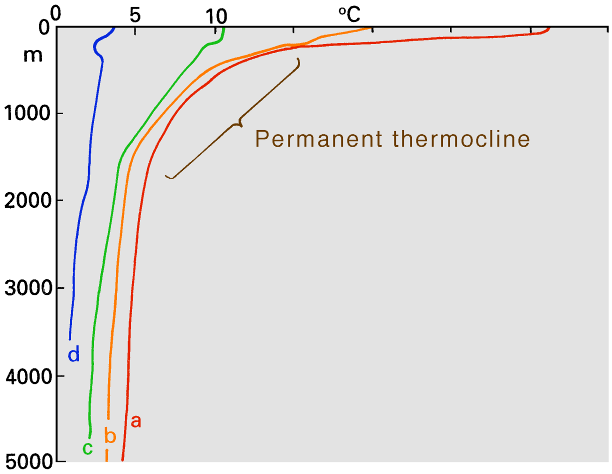


Fig. 6.1. Temperature profiles for different climatic regions near 150°W (Pacific Ocean).
(a) tropical (5°S),
(b) subtropical (35°S),
(c) subpolar (50°S),
(d) polar (55°S).
The temperature scale is correct for the polar profile; other profiles are shifted successively by 1°C. Note the shallowness of the warm surface layer and the absence of the permanent thermocline in the polar region. Data from Osborne *et al.* (1991).

It may seem strange that having spent five chapters on a discussion of temperate and tropical ocean dynamics, we now begin our regional discussion with a region that does not fit the earlier picture. However, our earlier discussion is not entirely irrelevant; it taught us how to get an idea of a region's dynamics by identifying the important forces and looking at their balance. The dynamics relevant for Antarctic waters are those of the "ocean interior" of Figure 3.1, i.e. geostrophy. In the tropics and subtropics, where density varies rapidly across the permanent thermocline, a small tilt of the thermocline produces a large horizontal pressure gradient. It is thus possible to balance all flow geostrophically across the thermocline and reduce velocities to virtually nothing below (this is the essence of the $1^1/_2$ layer model). In Antarctic waters density variations with depth are small and the pressure gradient force is more evenly distributed over the water column. As a result, currents are not restricted to the upper few hundred meters of the ocean but extend to great depth. Observations in Drake Passage show mean current speeds of 0.01 - 0.04 m s^{-1} at

Weddell Sea. They are bounded by the Mid-Atlantic and South-West Indian Ridges but at the 4000 m level well connected with the Argentine Basin in the western Atlantic and the basins of the western Indian Ocean. It is worth specific mention that at the 4000 m depth level the eastern Atlantic Ocean and the Pacific Ocean in general have no direct connection with the Southern Ocean.

More important for the dynamics than the basins are the ridges that separate them. The *Scotia Ridge*, which connects Antarctica with South America and contains numerous islands, is located about 2000 km east of Drake Passage, a narrow constriction where the southern tip of South America reaches 56°S while the Antarctic Peninsula extends to 63°S. At the 500 m depth level, the width of Drake Passage is about 780 km. The Scotia Ridge is generally less than 2000 m deep, but some openings exist at the 3000 m level. The combined effect of Drake Passage and the Scotia Ridge on the Circumpolar Current is quite dramatic: The current accelerates to squeeze through the gap and hits the obstacle at increased speed. It emerges highly turbulent and shifts sharply northward. The shift is a result of several factors, including deflection by the Coriolis force and changes in bottom depth along its path; however, the dynamics are too complex to be considered here in detail.

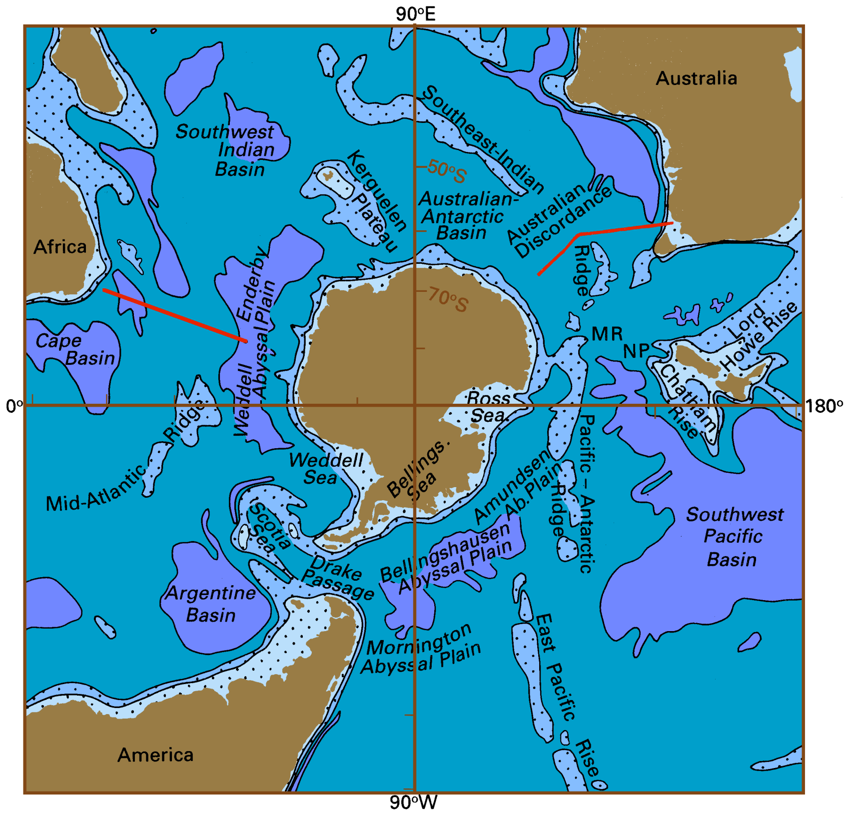
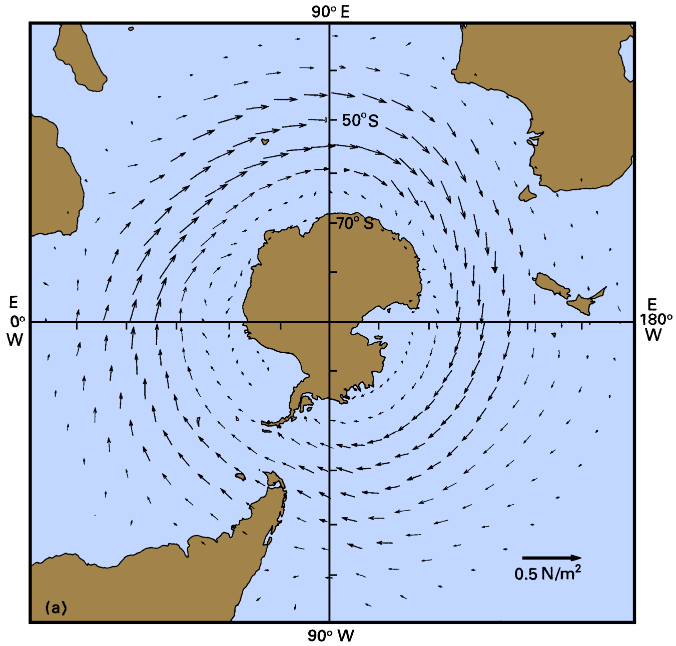


Fig. 6.2. Bottom topography of the Southern Ocean. The 1000, 3000, and 5000 m isobaths are shown, and regions less than 3000 m deep are shaded. Heavy lines near 20°E and 140°E indicate the location of the sections shown in Fig. 6.8. MR: Macquarie Ridge, NP: New Zealand Plateau.

storms but not necessarily the effect of wind bursts associated with squalls; they therefore have to be seen as reliable but low estimates. The distribution of curl($\boldsymbol{\tau}/f$) (Figure 6.5) has to be taken with similar caution.



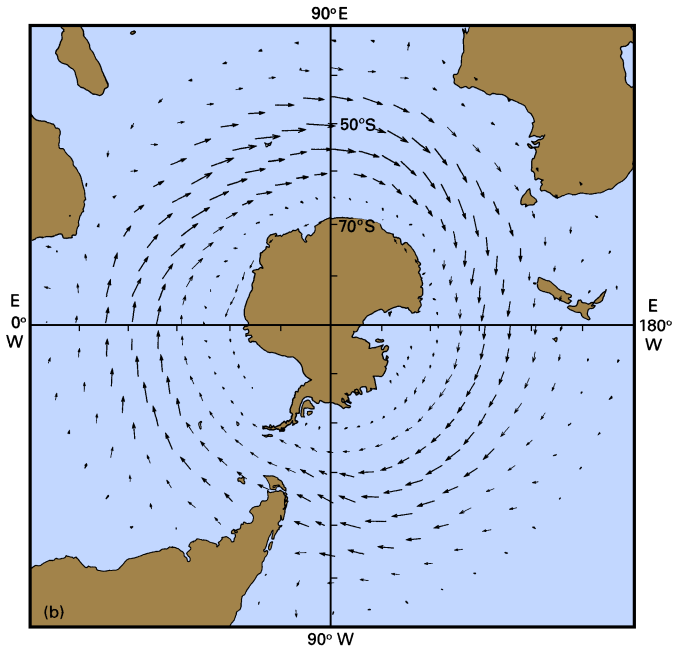


Fig. 6.4. (Right) Mean wind stress over the Southern Ocean (see Figure 1.4 for data sources).

(a) Annual mean;

(b) summer (December – February) mean;

(c, page 68) winter (June - August) mean.

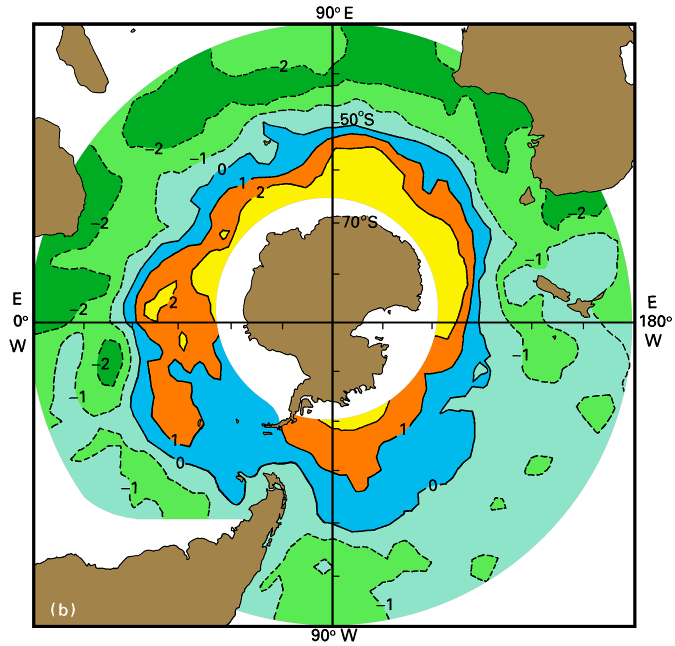
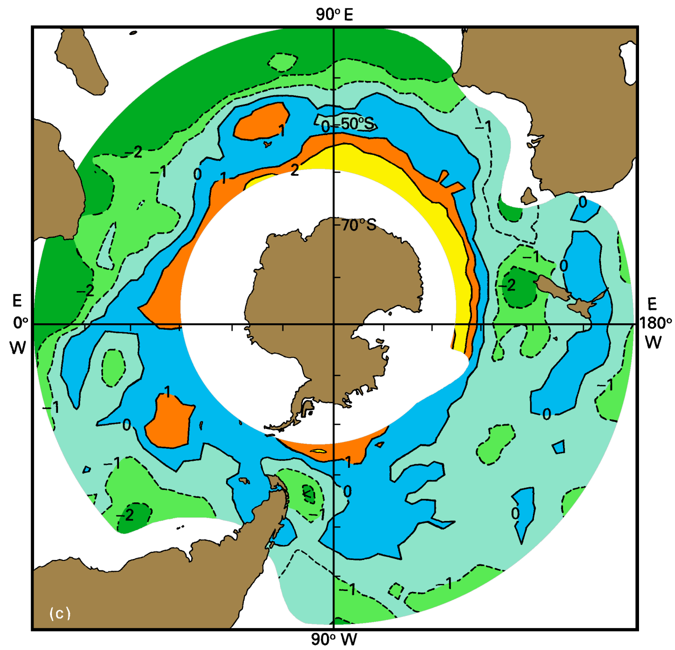


Fig. 6.5.
Mean curl(τ/f) over the Southern Ocean (10^{-3} kg m^2 s^{-1}, from Figure 4.3).
(a; page 68) Annual mean;

(b) summer (February - April) mean;

(c) winter (August - October) mean.

Note the uniformity of conditions despite variations in wind speed (Figure 6.4).



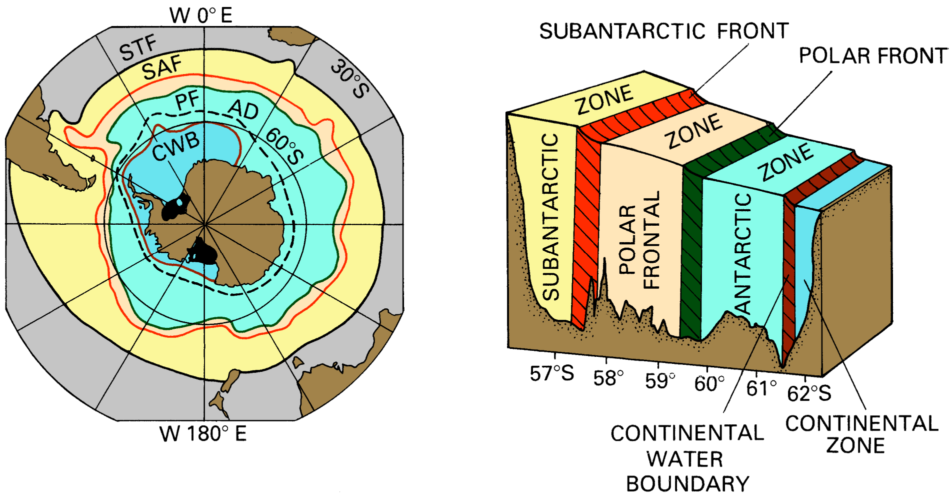


Fig. 6.7. Convergences and divergences of the Southern Ocean and a schematic representation of the zonation in the Southern Ocean. STF: Subtropical Front, SAF: Subantarctic Front, PF: (Antarctic) Polar Front, AD: Antarctic Divergence (dashed line), CWB: Continental Water Boundary. The vertical section is derived from data in Drake Passage where the zonation can extend to the bottom; it generally extends down to the level of Circumpolar Water. The dark regions indicate the Weddell and Ross Sea ice shelves.

Convergences and divergences

The Subtropical Convergence (STC) was introduced in Chapter 5 as the subduction region for Central Water (Figures 5.3 and 5.5). It is of some 1000 km meridional extent and corresponds to the region of negative curl($\boldsymbol{\tau}/f$) in Figure 6.5. The geographic definition of the Southern Ocean is tied to the southern limit of the STC, so it is desirable to define some line across the ocean surface as this limit. Observations show that in the southern STC temperature and salinity do not vary uniformly from north to south; there exists a narrow band around Antarctica where the salinity changes rapidly between 35.0 and 34.5 from north to south and temperatures drop rapidly as well. The feature, which runs parallel to the contour of zero wind stress curl some 5 - 10 degrees north of it, is called the *Subtropical Front*. Figure 6.7 shows three such features: the Subtropical Front, the Antarctic Polar Front indicative of the Antarctic Convergence, and the Antarctic Divergence. It has become accepted terminology to call the region between the continent and the Antarctic Polar Front the Antarctic Zone and the region between the Antarctic Polar and Subtropical Fronts the Subantarctic Zone. The positions of the fronts were constructed from data collected during passages of oceanographic vessels to Antarctica and back. No objective method was used in establishing the lines; rather, they represent an attempt of classical oceanography to interpret a patchy and noisy data set in the framework of a steady state. The observations indicate that at the surface the transition from the Subantarctic Zone to the Antarctic Zone occurs in two distinct steps rather than one, the so-called *Subantarctic Front* and the *Polar Front* proper (Figure 6.8). A complete zonation of the Southern Ocean therefore includes a Polar Frontal Zone between the Subantarctic and Antarctic Zones,

gradients does not extend simply in a zonal direction but includes meanders, convolutions and eddies of various sizes. They also indicate large shifts in the meridional position of the front, probably in response to variations in the wind stress field. An idea of these variations can be gained if it is recalled that the wind is geostrophic, too, and meridional shifts of the boundary between the Trades and the Westerlies are coupled with similar shifts in atmospheric isobars. Figure 6.10 shows, for the five years 1972 - 1977, the southernmost position of the 1015 hPa isobar, which on average (Figure 6.3) coincides with the position of the Subtropical Front (Figure 6.7). Seasonal variability appears small in the Indian, Atlantic, and eastern Pacific sectors; but in the western and central Pacific sector the difference between summer and winter can exceed 10 degrees in latitude. This is the same region where interannual variability is highest (Figure 6.10b), although the Indian sector also displays large differences, particularly in summer.

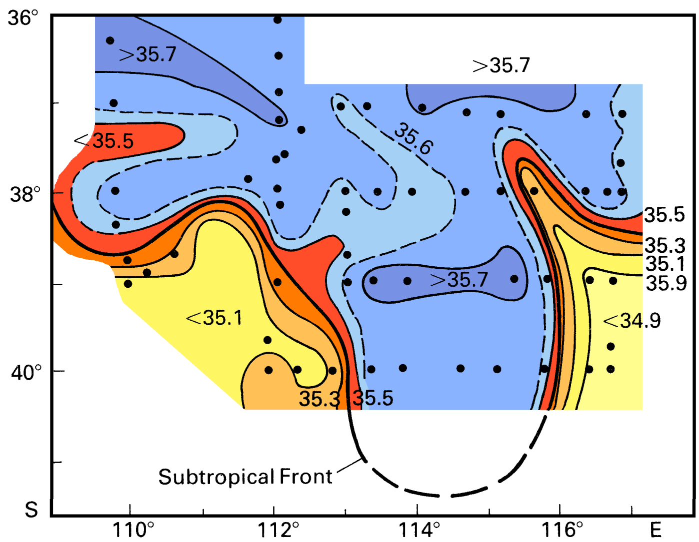


Fig. 6.9. (Left) Sea surface salinity in the eastern Indian Ocean showing meander formation in the Subtropical Convergence. The meander formed by the Subtropical Front was also seen in the track of a drifting buoy a few days before the cruise. Dots are station positions. From Cresswell *et al.* (1978).

How this variability in the atmospheric conditions translates into variability of the oceanic conditions is not known, but it can reasonably be argued that variations in the position of the Subtropical Front might be larger in regions of strong meridional shifts of the boundary between the Trades and the Westerlies than elsewhere. Comparison of synoptic surveys of the Subtropical Front (Figures 6.8a and 6.9) with the long-term mean (Figure 2.5a) reveals that at any particular time, property gradients across the front are much stronger than the maximum meridional gradient indicated by the mean property distributions. The fact that the front does not show up in the mean is most likely the result

below 4000 m depth. Poleward movement must therefore occur in the intermediate depth range for reasons of mass conservation, and this water must be lifted to the surface somewhere, to replace the water which sinks to form the Intermediate and Bottom Waters. Secondly, the fact that the Southern Ocean is continuous around Antarctica above the level of the Scotia Ridge precludes net southward movement of water above 2500 m.

To see this, consider the pressure distribution sketched in Figure 6.11. Along a circle of latitude through Drake Passage pressure must be continuous above the sill depth. Expressed in other words, a net zonal pressure gradient cannot exist, and there cannot be any *net* poleward geostrophic flow in the layer above the sill depth. Only below the depth of the sill can a zonal pressure gradient be supported (in the form of a pressure difference across Drake Passage, with the higher pressure in the west as sketched in Figure 6.11). If at that latitude the Westerlies produce northward Ekman transport in the surface layer, the water moving away from the Divergence can only be supplied be geostrophic southward flow below the sill depth of Drake Passage. The southward motion occurs principally just behind the sill, i.e. in the Atlantic Ocean. It is therefore mainly North Atlantic Deep Water which rises in the Antarctic Divergence. Integrated around Antarctica along 55°S, the northward Ekman transport - calculated from the wind stress data - is about 15 Sv, which is close to the southward flow of North Atlantic Deep Water.

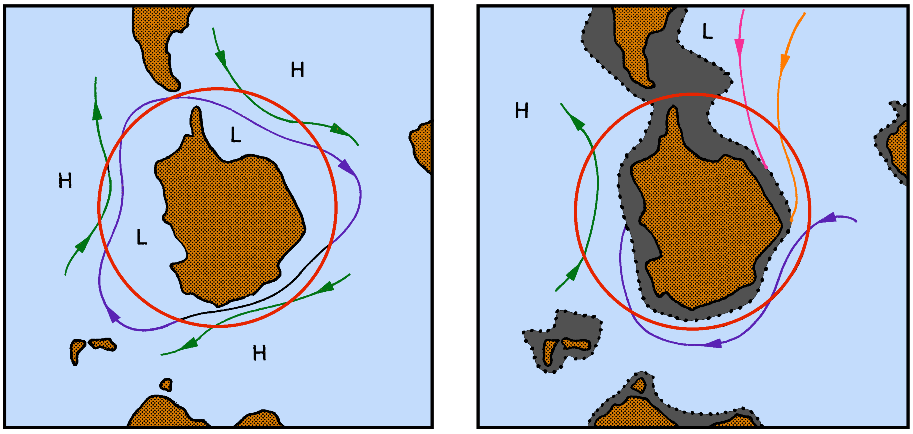


Fig. 6.11. Sketch of a pressure map in the Southern Ocean: (a) above, (b) below the Scotia Ridge sill depth. Above the sill depth, isobars have to be continuous around Antarctica. Geostrophic flow that enters the region encircled by a given latitude through Drake Passage has to leave it again. Below the sill depth, a pressure differential is supported across the sill; inflow into the region is possible.

The importance of the Scotia Ridge for the world ocean circulation was demonstrated in a numerical model (Gill and Bryan, 1971) who showed that the location and intensity of the Antarctic Divergence depends strongly on the sill depth in Drake Passage: a deepening of the passage would weaken the Divergence; closing the passage completely would suppress the Divergence entirely. Topography apparently also plays an important role in determining

$3.5 \cdot 10^6$ km^2 in summer and $18 \cdot 10^6$ km^2 in winter, of which 18% was open water. The extent of open water in otherwise ice-covered regions (polynya) varied greatly; large polynya were seen in the central Weddell Sea during three of the first four winters but not in later years. Icebergs can be found further north than sea ice, as far as 50°S at any season, their great mass preventing melting within a season.

Hydrology and water masses

Having established the main features of Southern Ocean dynamics we start the discussion of its hydrology by looking at a meridional section. Figure 6.8b shows salinity along a section in the eastern south Atlantic Ocean. The general southward and upward movement of high salinity North Atlantic Deep Water from depths below 2000 m is reflected in the shape of the isohalines. A substantial portion of this water comes to within 200 m of the surface at the Antarctic Divergence where it warms the surface water, melting the sea ice and the snow that falls on it, and sinks again at the Antarctic Polar Front. By the time it is subducted it can no longer be recognized as Deep Water, having been warmed and diluted by rain and snow on its northward passage, and is then known as the low salinity Antarctic Intermediate Water.

Modification of properties in the vicinity of the fronts is particularly strong during winter when convection creates a deep surface layer with water of uniform temperature and salinity in a region of usually strong horizontal and vertical gradients. Water in such layers is often called Mode Water, and the winter water in the Subantarctic zone is referred to as *Subantarctic Mode Water*. This water is not a water mass but contributes to the Central Water of the southern hemisphere. In the extreme east of the south Pacific Ocean it is responsible for the formation of Antarctic Intermediate Water (McCartney, 1977; England *et al*., in press).

The intense mixing processes which form the water masses of the Southern Ocean come out clearly if a T-S diagram of surface observations along a meridional line of stations is compared with T-S diagrams from stations in the Antarctic and Subantarctic zones (Figure 6.13). Both profiles start at the T-S point of Antarctic Bottom Water and end on the surface T-S curve but do this in distinctly different ways. In the Antarctic zone, water at the surface has very low temperatures, ranging down to the freezing point of -1.9°C, and low salinities as a result of ice melting in summer. In a hydrographic station in this zone (the dotted line in Figure 6.13) the influence of this low surface salinity is felt in the upper 100 - 250 m; this water is called *Antarctic Surface Water*. In the Subantarctic zone, surface water has a larger temperature and salinity range since seasonal variations of solar heating, rainfall, and evaporation become more important. The temperature range of this *Subantarctic Upper Water* spans 4 - 10°C in winter and 4 - 14°C in summer, with a salinity varying between 33.9 and 34.9 and reaching as low as 33.0 in summer as the ice melts. This produces a shallow surface layer of low salinity and an intermediate salinity maximum between 150 m and 450 m depth, as seen in the T-S data of the station from the Subantarctic zone (the full line in Figure 6.13). The difference between the full line and the dashed line in the T-S range of the Upper Water indicates that the figure compares data from different seasons. There are also variations between the various sectors of the zone, with lowest salinities in the Pacific and highest in the Atlantic sector.

The transformation of North Atlantic Deep Water into Antarctic Intermediate Water is seen in the T-S diagram as a mixing process between the deeper waters and surface water at the Antarctic Divergence. South of Australia Intermediate Water consists of some 60%

consequence for Bottom Water formation. In all other areas (the Weddell Sea, the Ross Sea, and probably also along the Adélie Coast and Enderby Land) the sinking occurs underneath the ice and is difficult to verify directly. There are, however, sufficient data which show the effect of the sinking. In the Weddell Sea, which probably contributes most to Bottom Water formation, the water as it sinks flows westward under the influence of the Coriolis

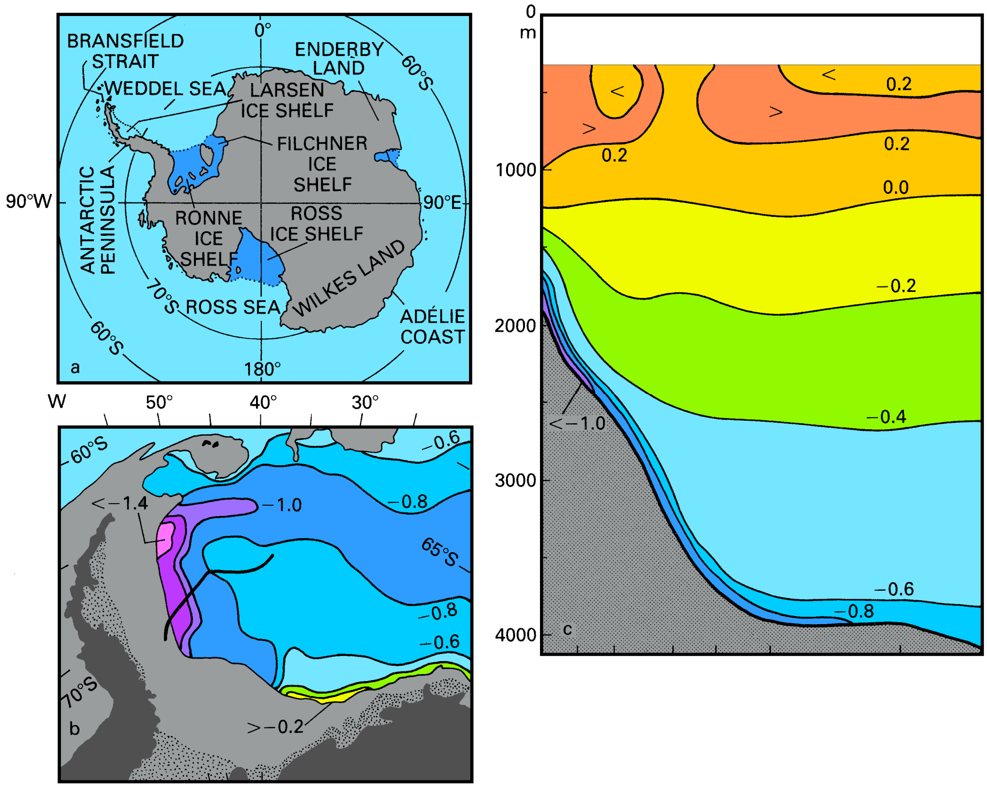


Fig. 6.14. Formation of Antarctic Bottom Water. (a) Locality map, including the regions where deep convection occurs, (b) bottom potential temperature (°C) in the Weddell Sea - the stippled area indicates ice shelf, and the edge of the shaded region is the approximate 3000 m contour, (c) a vertical section of potential temperature (°C) in the Weddell Sea. The position of the section is shown by the heavy line in (b). From Warren (1981a)

force, forming a thin layer of extremely cold water above the continental slope (Figure 6.14c). It mixes with the overlying water, which is recirculated with the large cyclonic eddy in the central Weddell Sea. This water, known as *Weddell Deep Water*, has very stable properties; its potential temperature usually is above 0.4°C and below 0.7°C. It is renewed by surface cooling and subsequent convection in the ice-free central part (polynya) of the Weddell Sea (Gordon, 1982). The opportunity for the water on the slope to mix with Weddell Deep Water is enhanced by the fact that sinking does not occur along the shortest possible path but in nearly horizontal motion along the slope. On reaching 65°S some of the water gets injected into the Circumpolar Current, where it continues to mix

Although much of the above discussion and all of the figures are based on modern data, the best way of summarizing the hydrography of the Southern Ocean is to reproduce a block diagram designed half a century ago. Figure 6.16 shows the interplay of strong zonal currents, meridional flow caused by deep convection, convergences and divergences, and water mass formation and spreading.

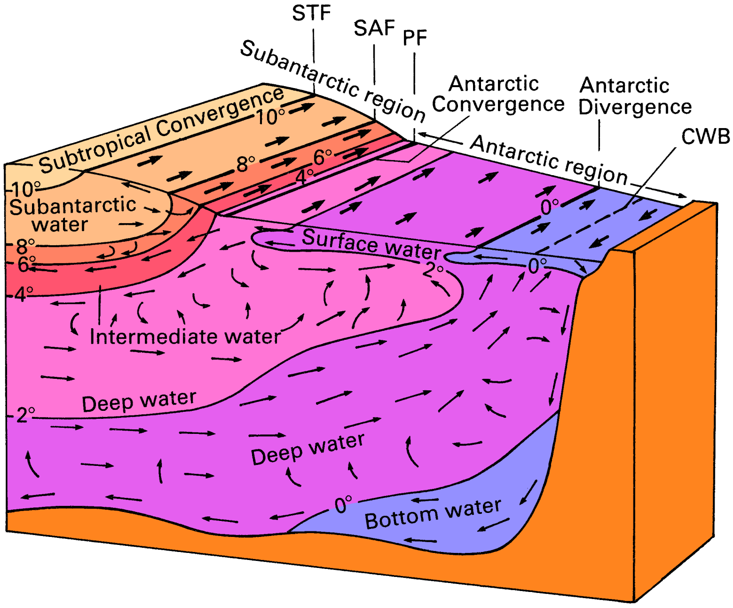


Fig 6.16. Block diagram of the circulation and Southern Ocean. From Sverdrup *et al.* (1942), with the addition of frontal locations. (STF: Subtropical Front, SAF: Subantarctic Front, PF: Polar Front, CWB: Continental Water Boundary).

Estimation of zonal and meridional flow

As mentioned earlier, the southward flow of North Atlantic Deep Water is estimated at 15 Sv from oceanographic data. It is opposed by northward flow of 2.5 - 5 Sv from the formation of Antarctic Bottom Water. Northward Ekman transport in the West Wind belt must make up the balance. Although most of the zonal transport occurs in the Atlantic sector, closure of the transport budget involves all three oceans. This is mainly caused by that part of the Ekman layer flow that contributes to the formation of Antarctic Intermediate Water; some of the Ekman transport therefore leaves the Antarctic sector and is recirculated through the Indian and Pacific Oceans before it can ultimately contribute to the replacement of the water sinking in the north Atlantic Ocean.

When it comes to estimating the zonal transport, the difficulty is in the determination of an acceptable depth of no motion. Again, the sill depth of the Scotia Ridge plays an important role. The observations of currents in Drake Passage mentioned earlier came from moorings which were deployed for a one-year period in 1978. They showed that below 2500 m depth there was much short term current fluctuation but little annual mean current. From these and later observations (Whitworth and Peterson, 1985) spanning a total period