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.

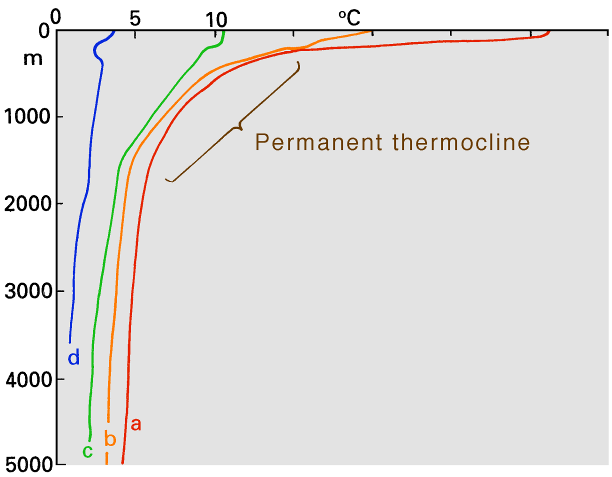


Fig. 6.1. Temperature profiles for different climatic regions near 150°W (Pacific Ocean).
(a) tropical (5°S),
(b) subtropical (35°S),
(c) subpolar (50°S),
(d) polar (55°S).
The temperature scale is correct for the polar profile; other profiles are shifted successively by 1°C. Note the shallowness of 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

2500 m depth, or 10-30% of the speeds observed at the 500 m level. It is therefore easy to see why the Circumpolar Current has the largest mass transport of all ocean currents: It moves a slab of water more than 2000 meters thick with speeds comparable to other surface currents.

Another aspect which makes the Antarctic region unique is the unlimited communication with all other oceans. The fact that the hydrology of all ocean basins cannot be understood without insight into what goes on in Antarctic waters, provides us with the reason why we are looking at this region first.

Many oceanographers refer to the region around the continent of Antarctica as the *Southern Ocean*. The International Hydrographic Bureau, which is the authority responsible for the naming of oceanic features, does not recognize a sub-region of the world ocean of that name but includes its various parts in the other three oceans. Thus, the area between 146°55'E and 67°16'W (about 40%) is considered part of the Pacific Ocean, the area from 20°E to 146°55'E (about 35%) part of the Indian Ocean, and the area between 67°16'W and 20°E (the remaining 25%) part of the Atlantic Ocean. These definitions were developed and agreed upon before the central features of ocean dynamics discussed in the previous chapters were established. From an oceanographic point of view, subdivisions of the world ocean should reflect regional differences in its dynamics. The Southern Ocean certainly deserves its own name on that ground. While we took care not to use the term Southern Ocean for the chapter heading, we shall adopt it in this book from now on and define it as the region south of a line where the tropical/temperate dynamics of Figure 3.1 break down. This occurs where the permanent thermocline reaches the surface, i.e. in the Subtropical Convergence. Realistically, this is not a well defined line but a broad zone of transition, between tropical/temperate and polar ocean dynamics. Its southern limit is marked by a frontal region of limited width known as the Subtropical Front, which will be discussed in detail following the sections on the topography and on the wind regime. Within the limitations set by the time variability of the Subtropical Front, the surface area encompassed by the Southern Ocean represents roughly $77 \cdot 10^6$ km^2, or 22% of the surface of the world ocean.

Bottom topography

Since we expect the Circumpolar Current to be present at all depths we can anticipate that in the Southern Ocean the topography of the ocean floor has a much larger impact on the currents, and on the hydrology in general, than in any other ocean. Figure 6.2 shows that the Southern Ocean consists of three major basins, where the depth exceeds 4000 m, and three major ridges. The *Amundsen*, *Bellingshausen*, and *Mornington Abyssal Plains*, sometimes collectively called the Pacific-Antarctic Basin, extend eastward from the Ross Sea towards South America and belong fully to the Pacific sector of the Southern Ocean. They are separated from the basins of the temperate and tropical Pacific Ocean by the Pacific-Antarctic Ridge and the East Pacific Rise in the west and the Chile Rise in the east. The *Australian-Antarctic Basin,* which is located in the Indian Ocean sector, stretches westward from the longitude of Tasmania to the Kerguelen Plateau. The South-East Indian Ridge separates it from the Indian Ocean to the north, but communication with the basins of the eastern Indian Ocean below 4000 m depth is possible via a gap at 117°E. The *Enderby* and *Weddell Abyssal Plains*, also known as the Atlantic-Indian Basin, form part of the Atlantic and Indian Ocean sectors and reach westward from the Kerguelen Plateau to the

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.

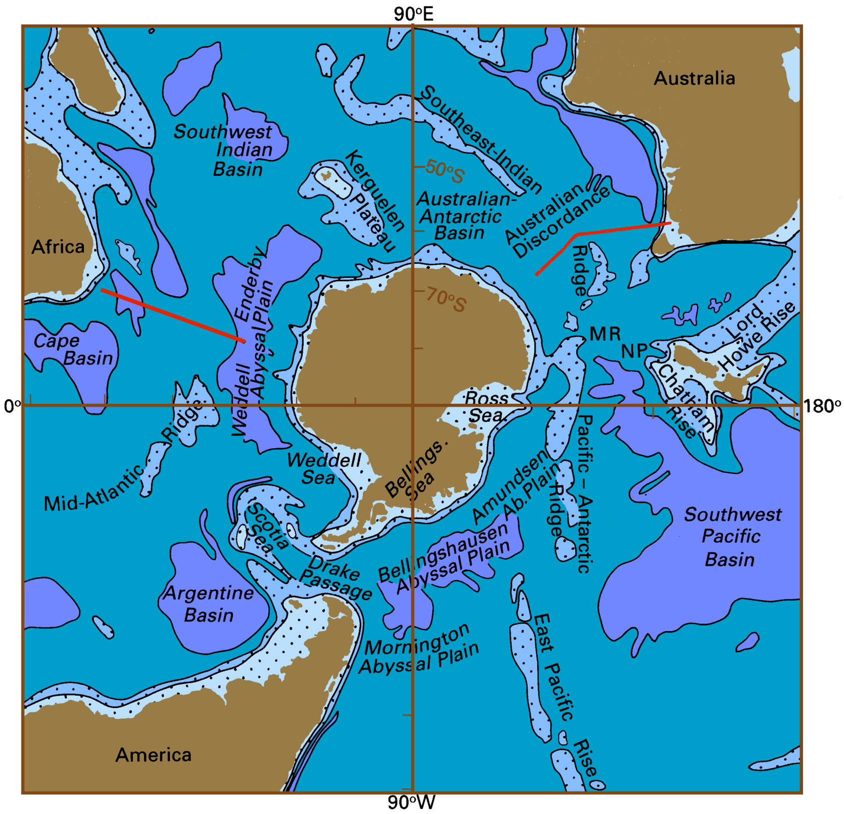


Fig. 6.2. Bottom topography of the Southern Ocean. The 1000, 3000, and 5000 m isobaths are shown, and regions less than 3000 m deep are shaded. Heavy lines near 20°E and 140°E indicate the location of the sections shown in Fig. 6.8. MR: Macquarie Ridge, NP: New Zealand Plateau.

The *Kerguelen Plateau*, which carries a few isolated islands, reaches and nearly blocks the 2000 m level, although most of its broad plateau is between 2000 m and 3000 m deep. It leaves a narrow gap between itself and Antarctica through which flow can occur below the 3000 m level. No significant departure of the current direction across the plateau is observed.

Finally, south of eastern Australia and New Zealand the *Macquarie Ridge*, the *Pacific-Antarctic Ridge*, and the *South-East Indian Ridge* combine to form the third obstacle to the Circumpolar Current that reaches the 3000 m level. The only gap at that depth is located just south of the Macquarie Ridge, at 59°S. On the other hand, much of the Macquarie Ridge reaches above 2000 m, and the ridge carries three islands. The *Campbell Plateau*, a large expanse of water less than 1000 m deep, reaches 54°S just east of the ridge. As a result of the complicated topography and Coriolis force influence, the Circumpolar Current shows a clear northward deflection in this region.

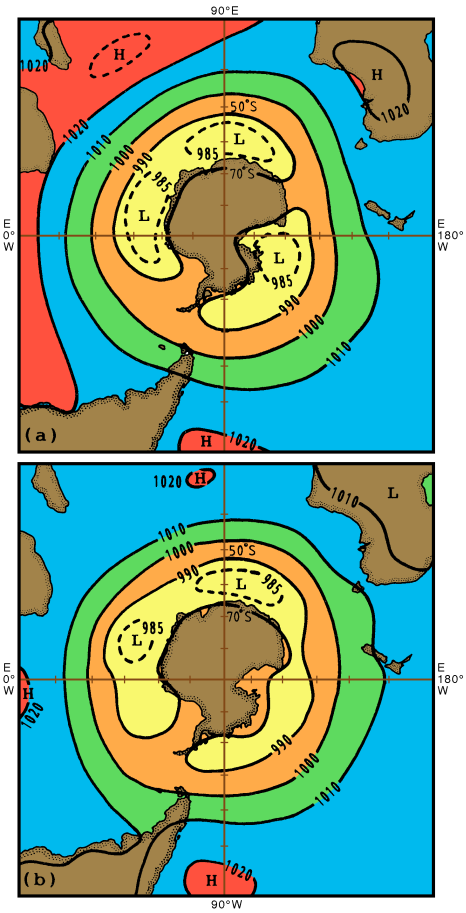
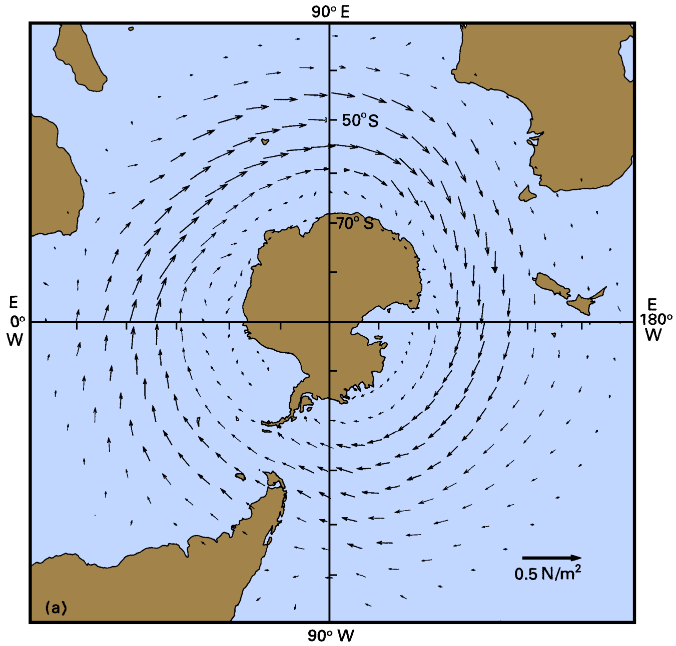


Fig. 6.3. (Left) Sea level air pressure (hPa) over the Southern Ocean. (a) July mean; (b) January mean. From Taljaard *et al.* (1969)

The wind regime

Most of the information required in this section is already included in Figures 1.2 - 1.4 and 4.3; but for the discussion of the Southern Ocean, projection on polar coordinates gives a better representation of the continuity around Antarctica. Figures 6.3 - 6.5 show the relevant maps. The surface pressure map (Figure 6.3) shows, in both summer and winter, a ridge of high pressure at about 25° - 35°S, with highest pressure over each ocean basin, and a trough at about 65°S, just north of the Antarctic continent. The mean geostrophic wind is evidently westerly between the trough and the ridge; but the mean pressure distribution strongly underestimates the mean wind stress which is proportional to the mean value of the square of the wind velocity. The circumpolar belt of westerly winds is dominated by frequent storms, which start in the north and angle southeastwards to die near 65°S where the winds turn into easterlies. It is these storms which determine the mean wind stress. The wind stress figures of Figure 6.4, which are based on the analysis of atmospheric observations over many years, include the transient 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.



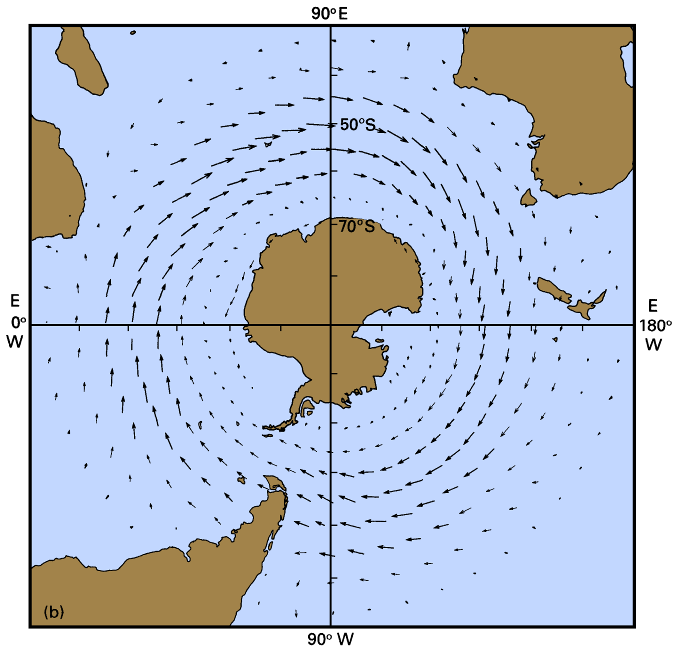


Fig. 6.4. (Right) Mean wind stress over the Southern Ocean (see Figure 1.4 for data sources).

(a) Annual mean;

(b) summer (December – February) mean;

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

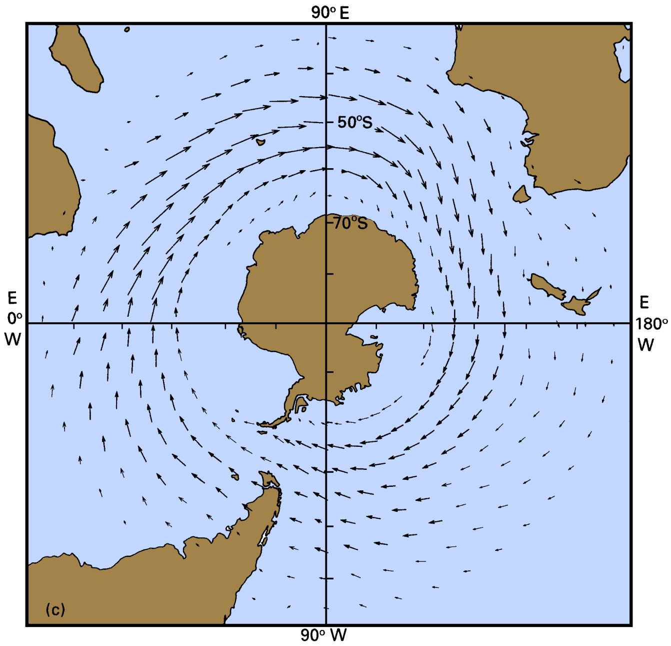
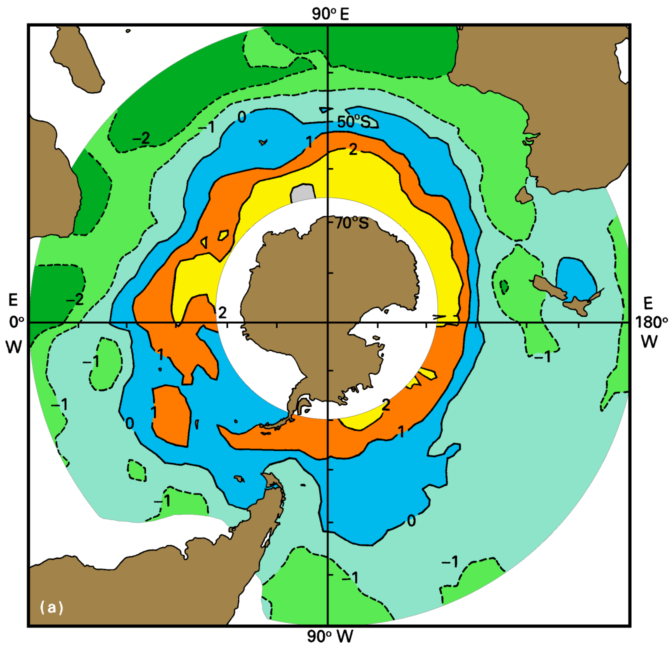


Fig. 6.4. (continued) Mean wind stress over the Southern Ocean (see Figure 1.4 for data sources).

(a, page 67) Annual mean;

(b, page 67) summer (December – February) mean;

(c, right) winter (June - August) mean.



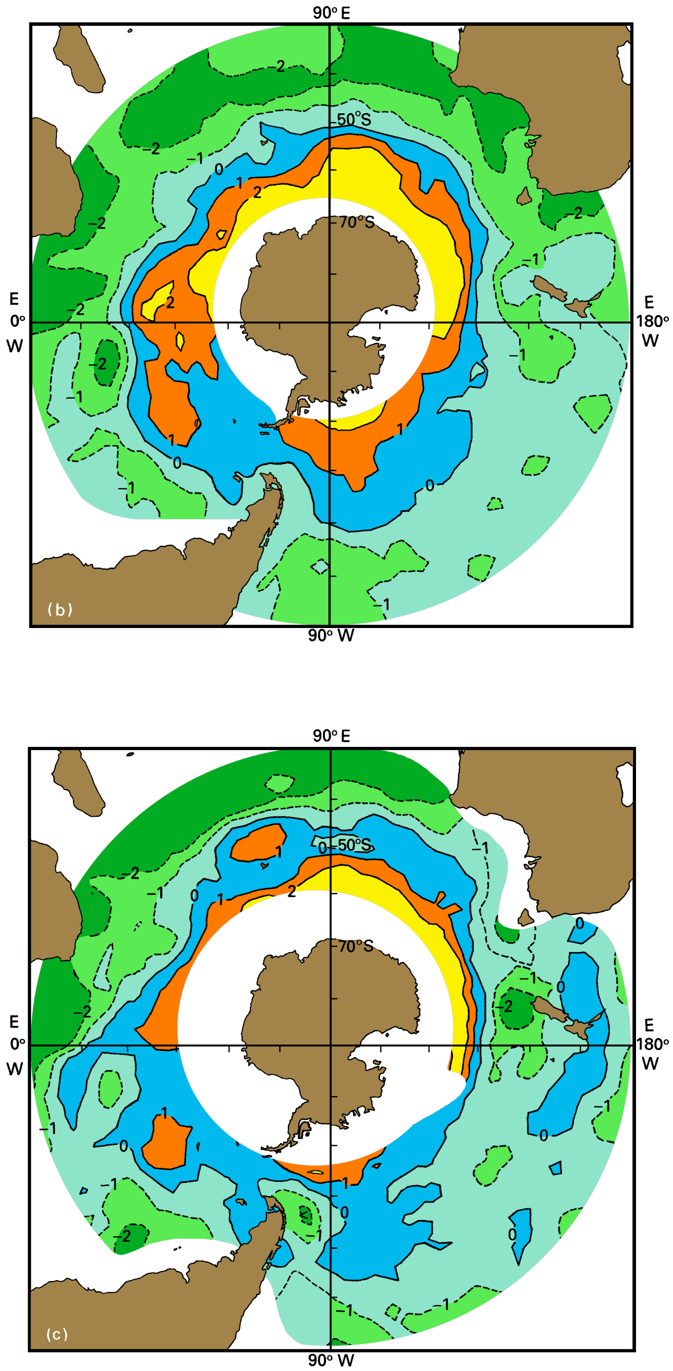


Fig. 6.5.
Mean curl(τ/f) over the Southern Ocean (10^{-3} kg m^2 s^{-1}, from Figure 4.3).
(a; page 68) Annual mean;

(b) summer (February - April) mean;

(c) winter (August - October) mean.

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

Close to the Antarctic continent the wind stress shows a reversal from eastward to westward, indicating the presence of Polar Easterlies along the coast. In the northern hemisphere the combination of West Wind Drift, Polar Easterlies, and meridional coastlines produces ocean currents known as the subpolar gyres (which will be discussed in later chapters). The Southern Ocean is devoid of meridional barriers, so the Polar Easterlies drive the *East Wind Drift*, a narrow coastal current which flows westward against the dominant eastward flowing Circumpolar Current. Both currents together are the southern hemisphere equivalent of the subpolar gyres.

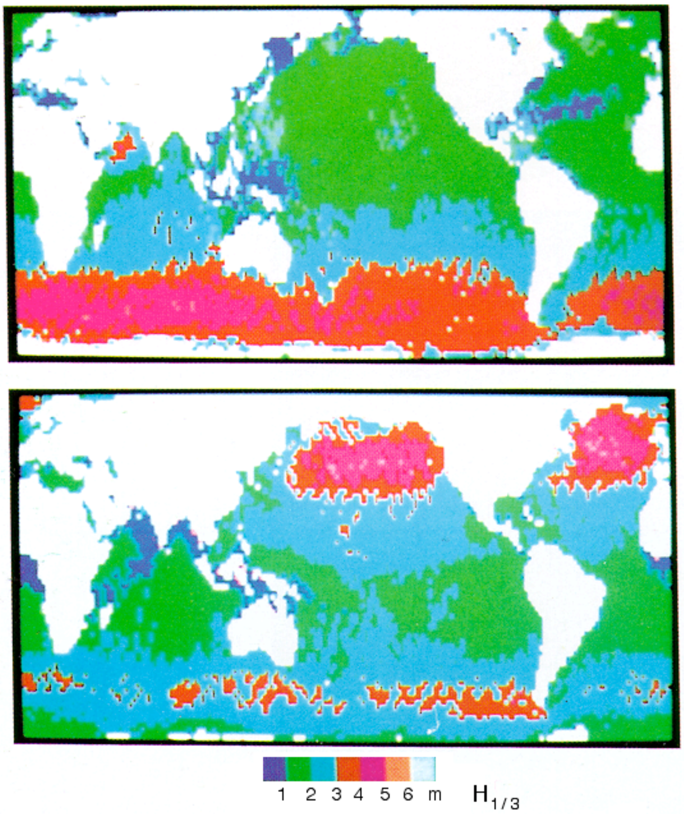


Fig. 6.6 Average significant wave height $H_{1/3}$ for the world ocean during the three-year period November 1986 – October 1989, determined from GEOSAT data. ($H_{1/3}$ is approximately the mean height of the 1/3 highest waves.) top: July, bottom: January. Note the prevalence of large waves ($H_{1/3}$ > 5m) in the Southern Ocean throughout the year, the increase in wave height during winter in both hemispheres, and the large waves in the western Arabian Sea during July. (See Chapter 11.)

One observation which stands out clearly in satellite data on the oceanic wave climate is the combined effect of consistently large wind speeds with little variation in wind direction, and no land barriers which could impede the build-up of a fully developed sea. The combination of infinite fetch around Antarctica and high average wind stress makes the Southern Ocean the region with the largest average wave height. Figure 6.6 shows results from GEOSAT, a satellite launched in March 1985 and active until October 1989. Wave data from GEOSAT were not available to non-military applications during the first eighteen months of its mission; the data used for Figure 6.6 are therefore restricted to a period between November 1986 and October 1989. This represents the best available estimate of annual mean conditions at present. The figure shows the Southern Ocean as a region of extremely high average wave height.

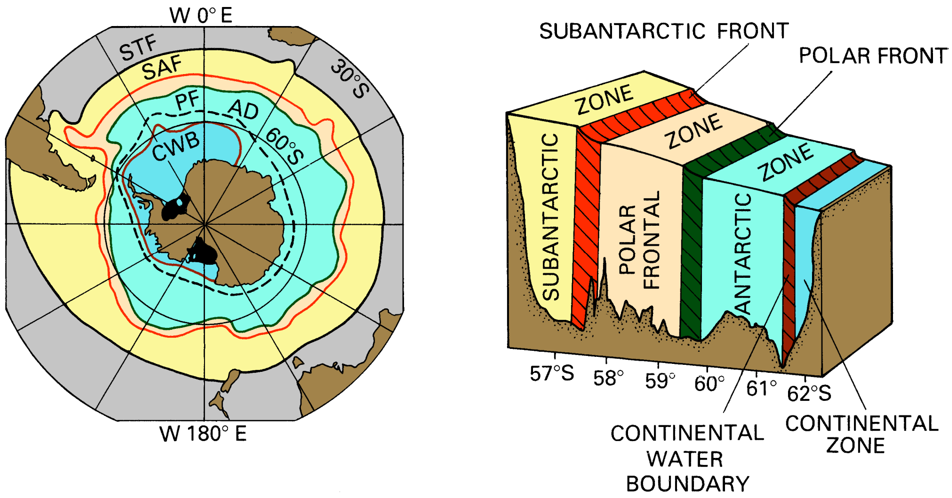


Fig. 6.7. Convergences and divergences of the Southern Ocean and a schematic representation of the zonation in the Southern Ocean. STF: Subtropical Front, SAF: Subantarctic Front, PF: (Antarctic) Polar Front, AD: Antarctic Divergence (dashed line), CWB: Continental Water Boundary. The vertical section 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, bounded by the two fronts (Figure 6.7). Close to the continent a separate water mass of uniform temperature and low salinity is found in the upper 500 m, separated from water of the Antarctic Zone by another frontal region, the continental water boundary.

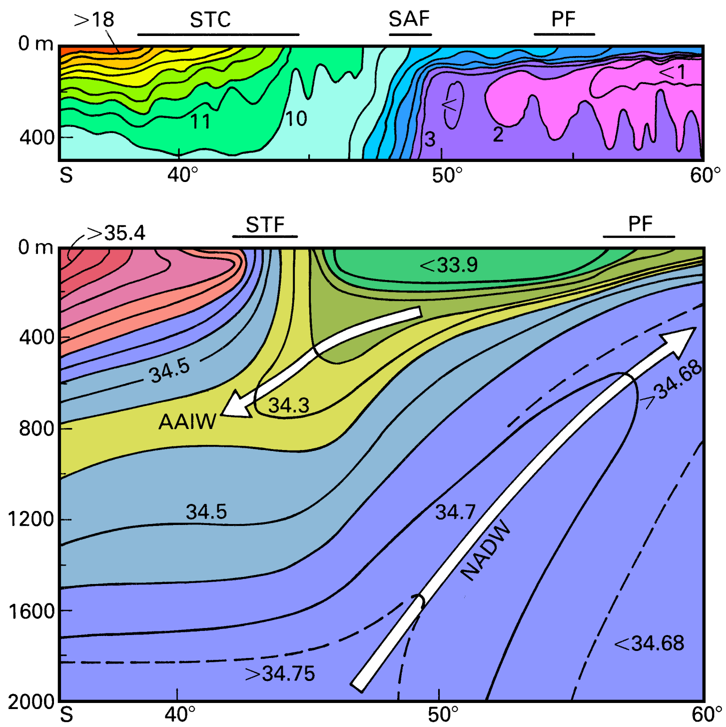


Fig 6.8. Hydrological sections through the Southern Ocean (summer conditions). (Top) Temperature section in the eastern Indian sector. The Polar Frontal Zone is indicated by the 3 - 9°C isotherms, and the split into the Subantarctic (SAF) and Polar (PF) Fronts by the crowding of isotherms at the surface around 7 - 9°C and 5 - 6°C. The Subtropical Front is indicated by the crowding of isotherms near 13 - 15°C within the Subtropical Convergence (STC). From Edwards and Emery (1982). (Bottom) Salinity section in the eastern Atlantic sector. Crowding of isohalines near 34.5 indicates the Subtropical Front. The Antarctic Divergence is located poleward of the section; near 65°S its salinity maximum is found just below 150 m. Upwelling of North Atlantic Deep Water (NADW) towards the divergence is indicated by the rise of the salinity maximum and sinking of Antarctic Intermediate Water (AAIW) from the Polar Front by the associated salinity minimum. Based on Bainbridge (1980). The different degree of detail between the two sections is the result of very different station density. See Fig. 6.2 for locations of sections.

In reality, the positions of the fronts and divergences vary greatly in time, and the intensity of sinking and rising motion is variable as well. There can be no doubt that the largest variability occurs in the Subtropical Front. Observations like those shown in Figure 6.9 usually indicate that the band of strong horizontal temperature and salinity 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.

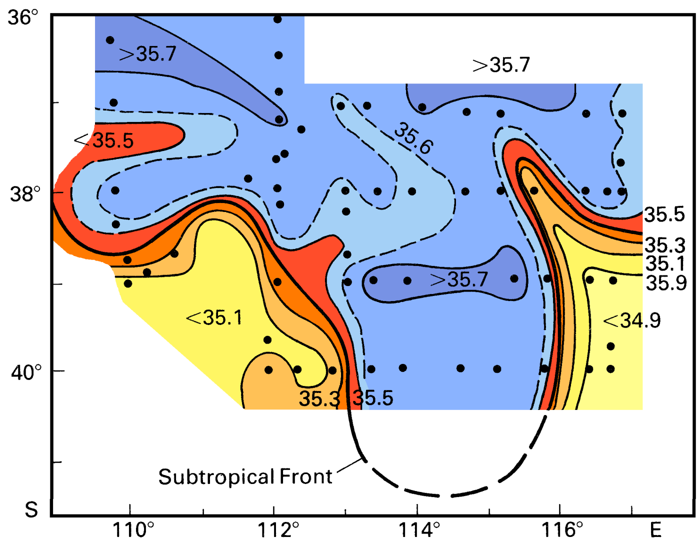


Fig. 6.9. (Left) Sea surface salinity in the eastern Indian Ocean showing meander formation in the Subtropical Convergence. The meander formed by the Subtropical Front was also seen in the track of a drifting buoy a few days before the cruise. Dots are station positions. From Cresswell *et al.* (1978).

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 of averaging over a relatively narrow frontal region which changes its position over time. The Antarctic Polar Front and the Divergence appear to be less mobile than the Subtropical Front and therefore show up stronger in the long-term mean, but they, too, display high variability at least in time. This is seen in the paths of buoys tracked by satellite which in the region between the Polar Front and the Divergence typically show rapid movement for several hundred kilometers, followed by longer periods of quite slow movement.

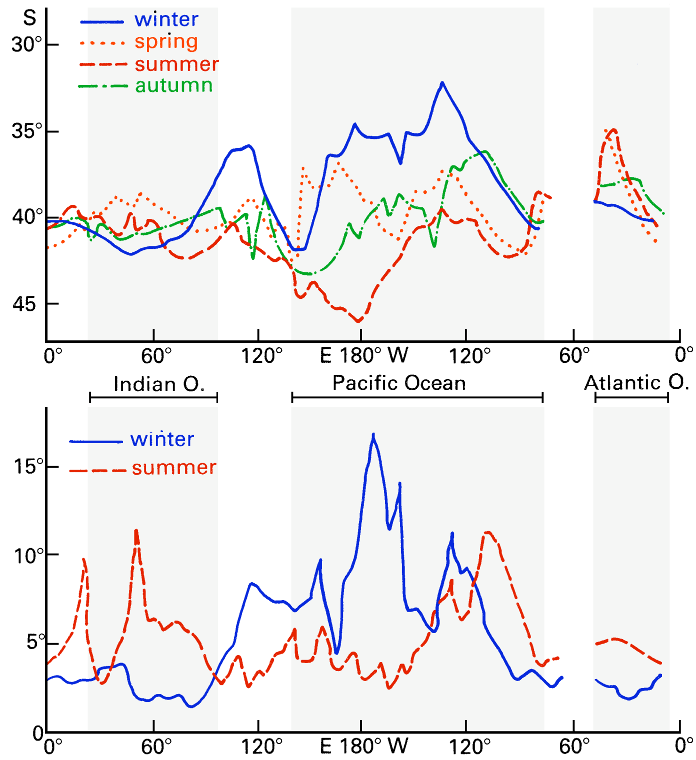


Fig. 6.10. (Right) Southernmost position of the 1015 hPa isobar during 1972-1977: (a) seasonal mean, (b) interannual variability, expressed as range (difference between largest northward and southward departure from the mean). Seasons are defined as: summer, December - March; autumn, April - May; winter, June - September; spring, October - November. Note the extreme seasonal and interannual variability in the Pacific Ocean. From Streten (1980).

The Antarctic Divergence, on the other hand, is linked with a meridional salinity maximum. At the surface the maximum is masked by low salinity from high precipitation and additional melting of ice, but it is clearly discernible below 150 m (Figure 6.8b). It is produced by upwelling of water with high salinity. The upwelling is unique in that the water reaching the surface comes from great depths; in the Atlantic Ocean, it is lifted from between 2500 m and 4000 m. The deep upwelling occurs for two reasons. Firstly, there is equatorward movement in the Intermediate Water and above, and again in the Bottom Water 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.

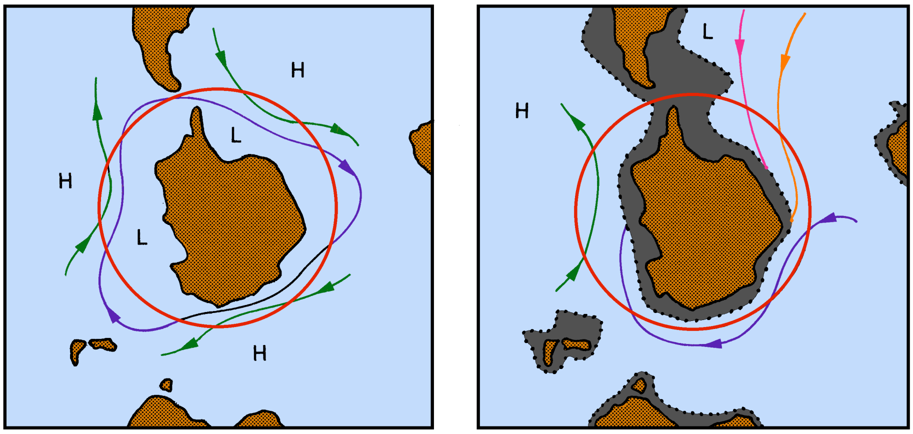


Fig. 6.11. Sketch of a pressure map in the Southern Ocean: (a) above, (b) below the Scotia Ridge sill depth. Above the sill depth, isobars have to be continuous around Antarctica. Geostrophic flow that enters the region encircled by a given latitude through Drake Passage has to leave it again. Below 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 the width and location of the various frontal zones. In the Indian Ocean sector, the Subantarctic and Subtropical Fronts merge near 95°E in the vicinity of the mid-ocean ridge (Edwards and Emery, 1982), and the Antarctic Polar Front merges with both above the Kerguelen Plateau near 65°E, eliminating the Subantarctic Zone completely (Gamberoni *et al*., 1982).

Precipitation and ice

If collecting wind data in the Southern Ocean is difficult, collecting rain and snowfall data on the deck of a ship in gale force seas is positively unpleasant. It is therefore not surprising that our information on the mass exchange between the atmosphere and the ocean is particularly scarce in that region. A broad band of relatively high precipitation surrounds Antarctica, centered at about 50°S, the regions of the strongest winds. Since evaporation in these high latitudes is very low, the mass budget between ocean and atmosphere is dominated by fresh water gain for the ocean.

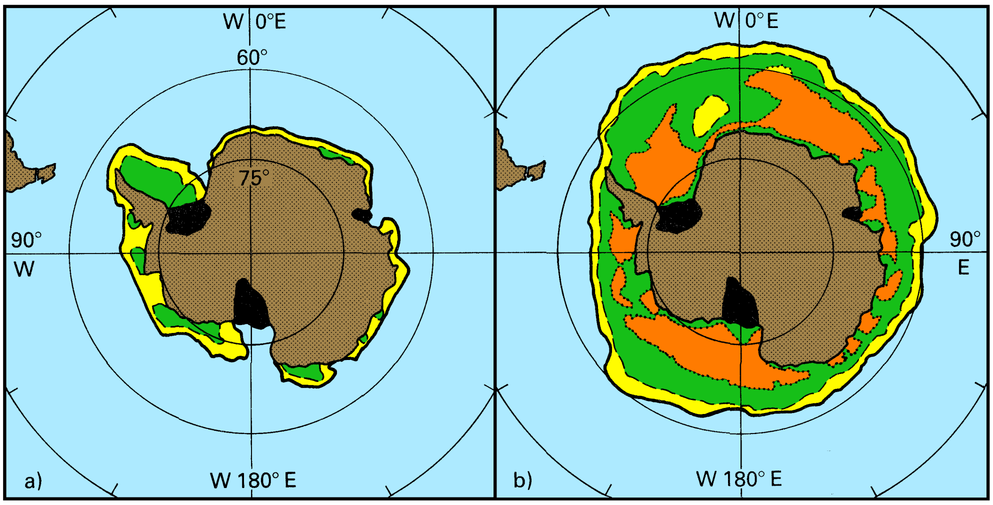


Fig. 6.12. Mean seasonal ice conditions in Antarctica, based on satellite data for 1973 - 1976. (a) Late summer (February), (b) late winter (October). Black areas indicate ice shelf (regions where the ice sits on the ocean floor): the ice shelves of the Weddell Sea at 50°W, the Ross Ice Shelf at the date line, and the Amery Ice Shelf at 70°E. The solid, broken, and dotted lines indicate ice coverage of 15%, 50%, and 85%.

The effect of precipitation on sea surface salinity is augmented by the loss of salt from the surface in winter, as brine rejected by sea ice sinks to great depth, and the melting of ice in summer; this explains the low salinity of near-surface water in the Antarctic region (Figure 2.5d). The sea ice does not extend far past Antarctica in summer, but it covers an area the size of the continent in late winter (Figure 6.12). Estimates of ice coverage from satellite data (Gloersen and Campbell, 1988) give the average ice extent for 1978-1987 as

$3.5 \cdot 10^6$ 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%

Subantarctic Upper Water and 40% Circumpolar Water; only in the extreme eastern south Pacific Ocean and in the Scotia Sea of the Atlantic sector, where the T-S properties of Subantarctic Mode Water resemble those of Antarctic Intermediate Water, is Intermediate Water apparently formed in direct contact with the atmosphere. Formation of *Antarctic Circumpolar Water* through mixing of North Atlantic Deep Water and Antarctic Bottom Water is indicated by the straight line formed by T-S data between the Deep Water and the water on the Antarctic shelf.

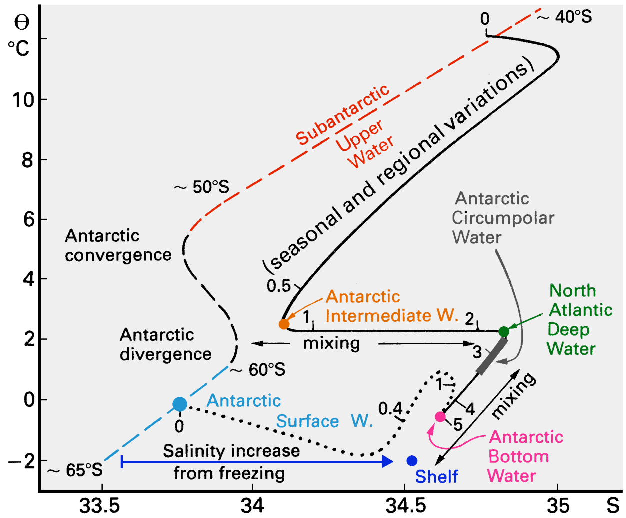


Fig. 6.13. A T-S diagram for a station in the Subantarctic (full line) and in the Antarctic zone (dotted line), and a T-S diagram from surface observations along crossings of the Antarctic Polar Front and Divergence (dashed line). Depth on the vertical T-S profiles is indicated in km.

It has of course to be remembered that the deep vertical and meridional circulation occurs on the background of intense zonal flow. This is particularly evident when the formation of Antarctic Bottom Water is investigated in detail. Its origin lies in deep convection at the continental shelf driven by the freezing of sea ice (Figure 6.13), but its final properties are shaped during intense mixing with the water of the Circumpolar Current (Circumpolar Water) while sinking to the bottom. It is therefore incorrect to say that the formation process for Antarctic Bottom Water is convection alone; rather, it is a combination of convection and subsurface mixing. It is seen that the properties of Circumpolar and Bottom Water are defined in a process of mutual interaction which draws on the properties of North Atlantic Deep Water as well.

The areas where convective sinking occurs (Figure 6.14a) are believed to be relatively limited in size. The only location where sinking to the ocean floor by convective overturning has been identified from data is Bransfield Strait; but the water which sinks there is collected in an isolated trough of between 1100 m and 2800 m depth and of little 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

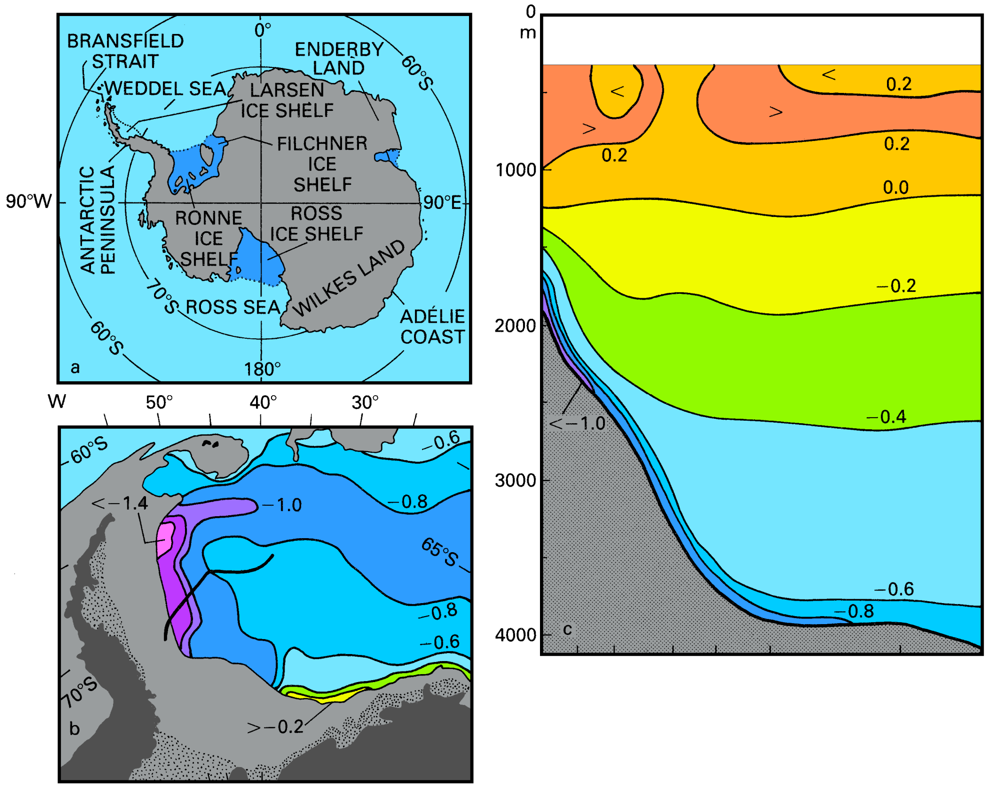


Fig. 6.14. Formation of Antarctic Bottom Water. (a) Locality map, including the regions where deep convection occurs, (b) bottom potential temperature (°C) in the Weddell Sea - the stippled area indicates ice shelf, and the edge of the shaded region is the approximate 3000 m contour, (c) a vertical section 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 with the Circumpolar Water. The properties of the sinking water are somewhat known from ships that have been trapped in the ice over winter. They measured bottom potential temperatures around the freezing point (about -1.9°C) and salinities of 34.7 - 34.9. By the time the water leaves the Weddell Sea its temperature has risen to -0.8°C. The further path of Antarctic Bottom Water can be followed by looking at the potential bottom temperature map (Figure 6.15); it indicates the Adélie Shelf and the Ross Sea as other important regions where cold - and saline - water is injected from the surface. Eventually, the water spreads from the Circumpolar Current (i.e. with the properties of Circumpolar Water) into all three oceans. At that stage its properties are best described as 0.3°C and 34.7 salinity.

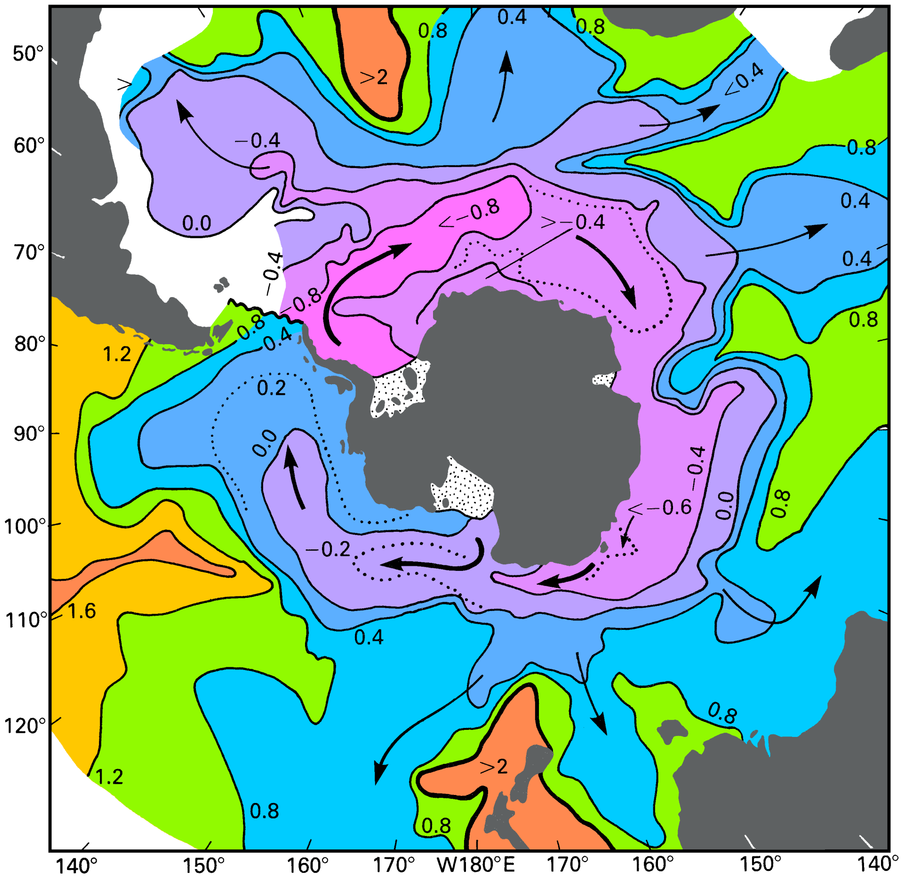


Fig. 6.15 Bottom potential temperature in the Southern Ocean. Isotherms are drawn every 0.4°C, with the exception of the New Zealand Plateau and the Mid-Atlantic Ridge where the 2°C isotherm follows the 0.8°C isotherm. The arrows show inferred movement of Antarctic Bottom Water. Southward intrusions of high potential temperatures reflect ridges less than 4000 m deep. Northward extensions of low potential temperatures indicate movement of Antarctic Bottom Water over sills; the deeper the sill, the lower the temperature. Adapted from Gordon (1986b).

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.

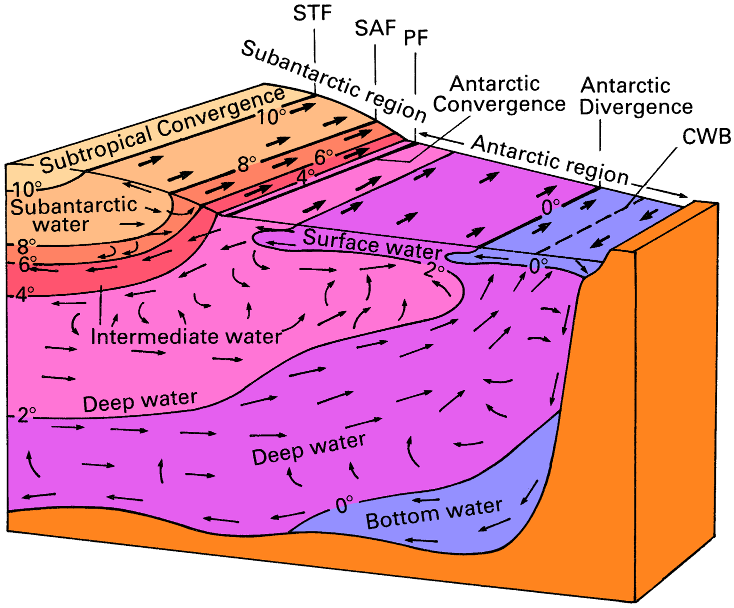


Fig 6.16. Block diagram of the circulation and Southern Ocean. From Sverdrup *et al.* (1942), with the addition of frontal locations. (STF: Subtropical Front, SAF: Subantarctic Front, PF: Polar Front, CWB: Continental Water Boundary).

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 of about four years, the mass transport for the Circumpolar Current through Drake Passage was determined as 128 ± 15 Sv, with maximum variations of over 50 Sv within two months and an indication of a winter minimum in July. Most of the mean transport could be accounted for by geostrophic flow above an assumed depth of no motion of 2500 m. The 50 Sv fluctuations were associated mostly with changes in sea level gradient across the passage with very little density change; the corresponding current variations were therefore uniform in depth. Earlier observations, for a one-year period and again in Drake Passage (Bryden and Pillsbury, 1977), gave an average of 139 Sv but a total range between 28 and 290 Sv. More definite estimates will become available with the completion of World Ocean Circulation Experiment (WOCE). Current speeds are generally low, between 0.05 and 0.15 m s^{-1}, because of the large width and depth of the current, although 0.5 m s^{-1} and even 1 m s^{-1} have been observed in jets associated with frontal regions on occasions. Because of their enhanced horizontal density gradients and associated geostrophic currents, the frontal regions carry most of the transport; observations from Drake Passage (Nowlin and Clifford, 1982) indicate that above 2500 m, 75% of the total flow occurs in the frontal zones, which occupy only 19% of the cross-sectional area.

Estimating the meridional heat flux, a key element in the global heat budget, is even more difficult. The transfer of heat from the Circumpolar Current to the atmosphere has been estimated (Gordon and Owens, 1987) as $3 \cdot 10^{14}$ W. This heat loss must be balanced against poleward oceanic heat flux across the current. The primary movers of heat appear to be the large eddies generated by the current in interaction with topography. Little is known about the frequency of eddy formation and the life expectancy of individual eddies. Satellite altimeter observations (Figure 4.8) imply that they are not uniformly distributed along the path of the Circumpolar Current but are more frequent east of the Scotia Ridge and in the region of the Macquarie Ridge (between Tasmania and New Zealand). These regions therefore are likely to play a major role in the poleward transport of heat. Temperature records from Drake Passage (Figure 6.17) indicate the passage of five cyclonic (i.e. cold core) eddies and one anticyclonic (warm core) eddy over a period of eight months. The eddies were of 30 - 130 km diameter, extended to at least 2500 m depth and were moving northward across the Circumpolar Current at about 0.04 m s^{-1}. This northward movement of (on average) cold water has to be compensated by poleward movement of comparatively warmer water and therefore represents a poleward flux of heat. Provisional estimates (Keffer and Holloway, 1988) give values of $1.3 - 5.4 \cdot 10^{14}$ W, enough to balance the estimated heat loss to the atmosphere.

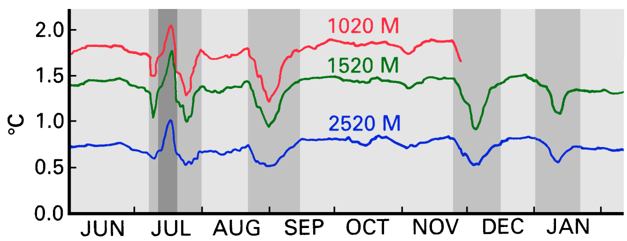


Fig. 6.17. A time series of temperature (°C) obtained at a mooring in central Drake Passage, showing the passage of five cold-core rings (medium shading) and one warm-core ring (dark shading). From Pillsbury and Bottero (1984).