CURRENT SYSTEMS IN THE SOUTHERN OCEAN

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Summary

The Southern Ocean, encircling Antarctica, plays a major role in shaping the characteristics of the global ocean. It provides the most significant inter-ocean conduit by which waters of the three major oceans, the Atlantic, Pacific and Indian, can intermingle, acting to diminish their differences in temperature, salinity, and chemical properties. The most prominent current is the Antarctic Circumpolar Current, which transfers about 134 million $m^3 s^{-1}$ of sea water from west to east within a latitudinal range from 50° to 60°S. North of the Antarctic Circumpolar Current are the poleward limbs of the large subtropical gyres of the southern hemisphere, referred to as the South Atlantic, South Indian, and South Pacific Currents. Within large embayments of Antarctica, notably the Weddell and Ross Seas, south of the Antarctic Circumpolar Current are large clockwise flowing gyres. The Weddell Gyre carries about 30–50 million $m^3 s^{-1}$ of water. Along the continental margin of Antarctica is the coastal current that advects water from east to west. The coastal current is directed towards the north along the east coast of Antarctic Peninsula, forming the western boundary of the Weddell Gyre.

At the northern tip of the Antarctic Peninsula the coastal current is directed into the open ocean. The coastal waters injected into the open ocean separate the Antarctica Circumpolar Current from the Weddell Gyre, in what is called the Weddell-Scotia Confluence. Besides ocean currents flowing on nearly horizontal planes, the Southern Ocean experiences major overturning of ocean water. Overturning is forced by the production of dense surface water along the margins of Antarctica, leading to the formation of Antarctic Bottom Water. Within the Antarctic Circumpolar Current, at the Polar Front,

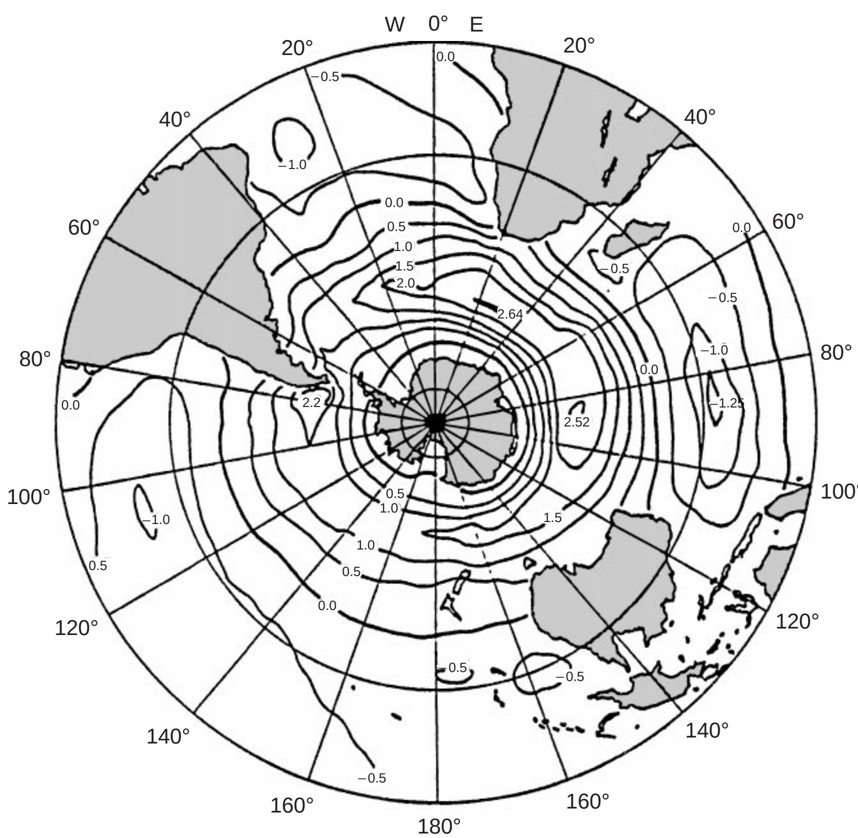

Figure 1 Wind stress in $N m^{-2}$. (Reproduced with permission from Nowlin and Klinck, 1986.)

surface waters sink under the more buoyant surface water to the north, forming Antarctic Intermediate Water, a low salinity intrusion spreading at a depth of nearly 1000 m under the main thermocline of subtropical ocean. The horizontal and vertical circulation influences the distribution of sea ice, which in turn modifies the heat, freshwater, and gas exchange between the Southern Ocean and polar atmosphere.

Introduction

Ocean currents are the product for the most part of the stress exerted on the sea surface by the wind. The winds are strong over the Southern Ocean, particular within the Indian Ocean and Australian sectors (**Figure 1**) and therefore drive a vigorous circulation (**Figure 2**). Strong westerlies (wind directed from west to east) extend from the subtropical high atmospheric pressure near 30°S, a latitude often used to define the northern limits of the Southern Ocean, to a belt of low atmospheric pressure at 65°S. South of 65°S the winds are easterlies, marking the northern edges of the polar high pressure over Antarctica.

Density changes of surface water induced by sea–air fluxes of heat and fresh water, often involving sea ice within the Southern Ocean, also produce circulation. However, buoyancy (sometimes referred to as thermohaline), circulation is sluggish and mainly occurs within the meridional vertical plane, as dense water sinking forces slow, compensatory upwelling of less dense resident water. Sinking of dense waters along the continental margins of Antarctica results in Antarctic Bottom Water.

Ocean currents are for the most part in equilibrium with the distribution of density within the ocean (**Figure 3**) satisfying approximately the so-called 'thermal wind equation' (*see* **Elemental Distribution: Overview; Ocean Circulation.**) Along the Greenwich meridian the surface of equal density, or isopycnals, rise up towards the sea surface as latitude increases to the south. Strongly sloped isopycnals are coupled to strong ocean current, more

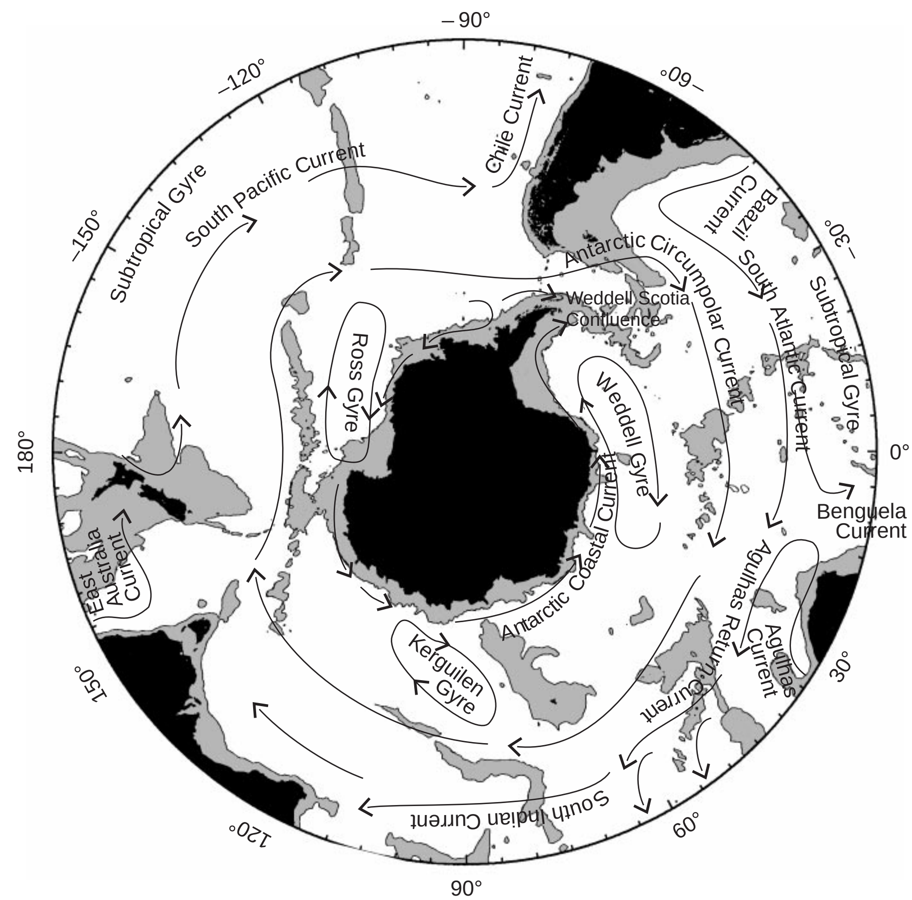

Figure 2 Schematic of general circulation of the Southern Ocean. Land is black; the shaded area marks ocean depths of < 3000 m.

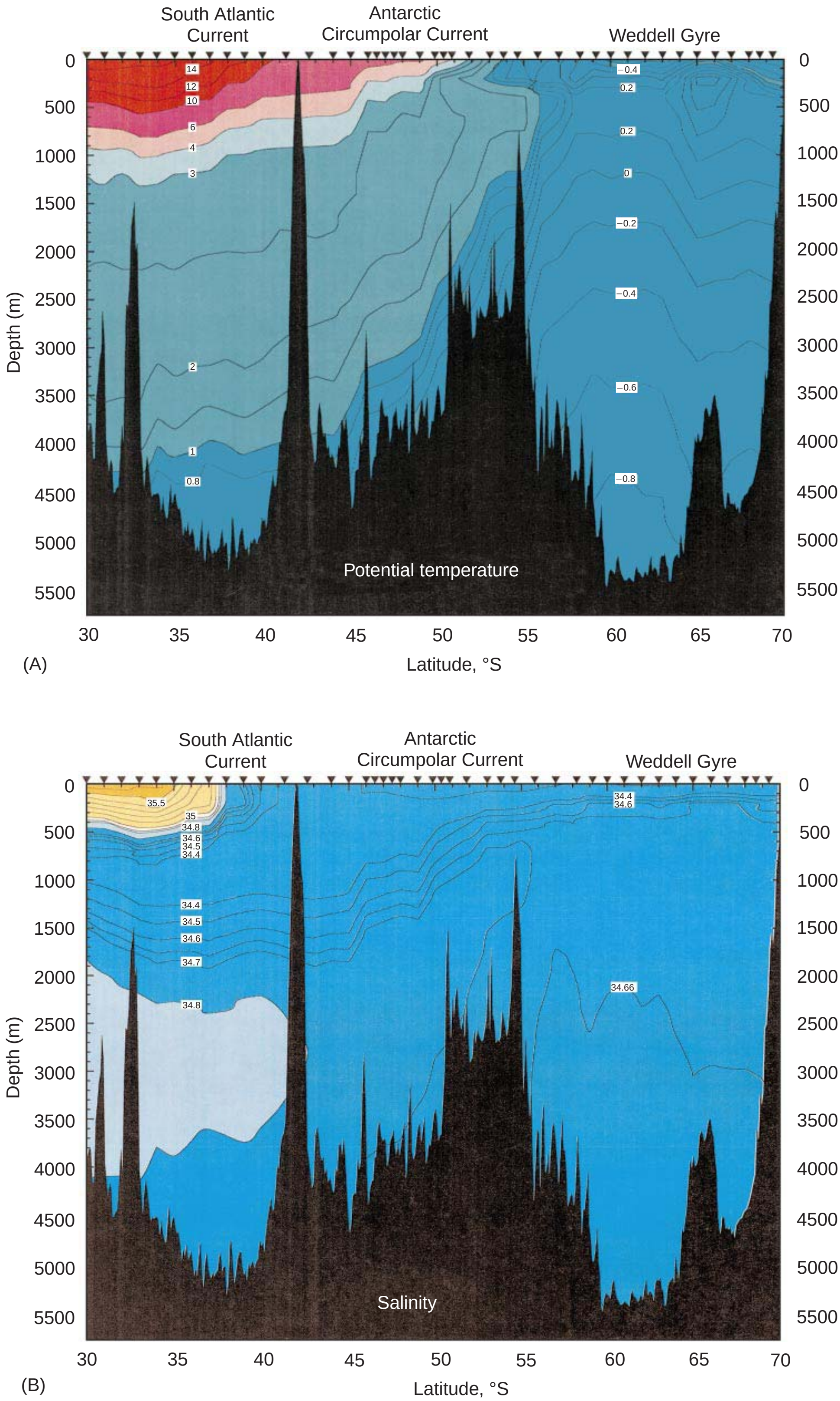

Figure 3 Potential (A) temperature, (B) salinity and (C) density (sigma-0) along the Greenwich meridian.

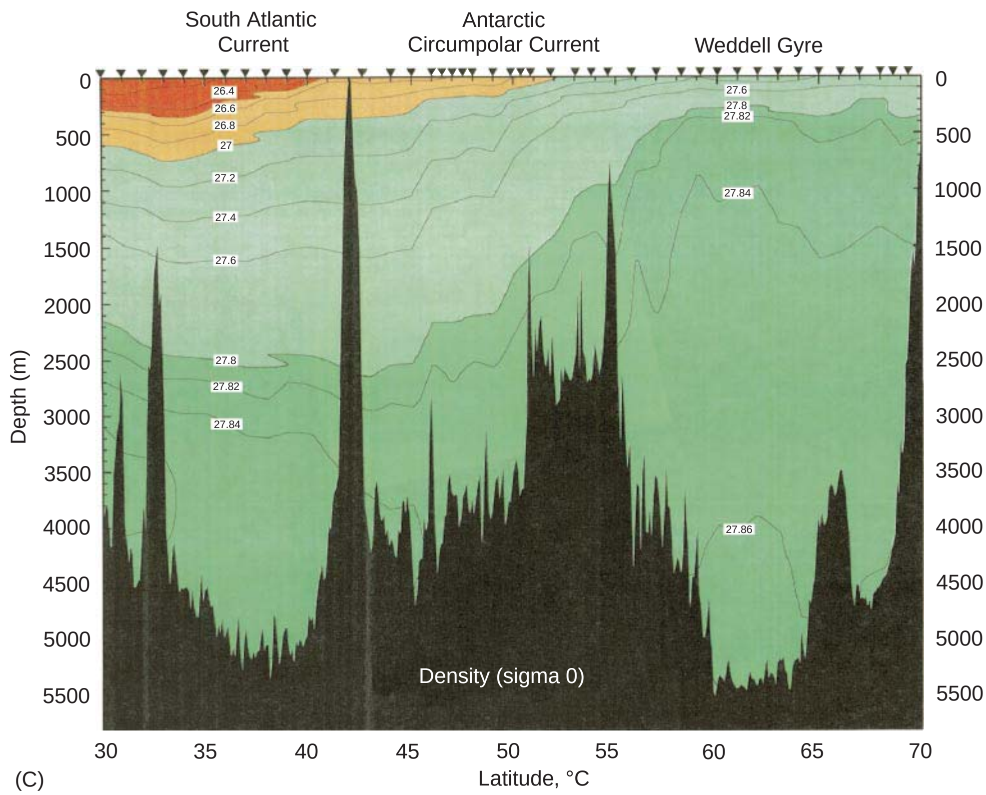

Figure 3 *Continued*

precisely to strong geostrophic ocean currents, relative to the seafloor. As a rule of thumb, in the southern hemisphere higher density water occurs to the right of the direction of the ocean current. Hence the increasing density as latitude increases is linked to west to east flow of water. Along the margin of Antarctica the descent of isopycnals marks a flow towards the east. Regions of rapid changes in temperature, salinity or density mark the positions of ocean fronts, often coinciding with a strong ocean current.

Maximum westerlies in the wind occur near 55°S, which roughly coincides with the axis of the Antarctic Circumpolar Current. To the south of this latitude, wind-induced northward Ekman transport of surface water results in a wide region of upwelling. North of 55°S the Ekman transport diminishes. This causes a region of surface water convergence. Near 55°S surface water sinks under the more buoyant surface water to the north, producing Antarctic Intermediate Water. Antarctic Intermediate Water forms a low salinity layer found at the base of the thermocline of the subtropical southern hemisphere regions. Upwelling poleward of the maximum westerlies brings deeper water to the sea surface to compensate for the sinking of Antarctic Bottom Water and Antarctic Intermediate Water. The upwelling also drives two large clock-wise-flowing, cyclonic Gyres within the large embayments of Antarctica, marking the Weddell and Ross Seas (**Figure 2**) and a smaller one east of Kerguelen Plateau.

Antarctic Circumpolar Current

The most prominent current of the Southern Ocean is the west to east flowing Antarctic Circumpolar Current lying within a latitudinal range from 50° to 60°S. It is the greatest ocean current on the Earth, covering a distance of 21 000 km, with an average transport through the Drake Passage (between South America and Antarctic Peninsula) of 134 million $m^3 s^{-1}$ (134 Sv). The transport varies with time mirroring variations in the circumpolar wind field, from about 100 to 150 million $m^3 s^{-1}$. Transport is enhanced south of Australia by return of water to the Pacific Ocean lost to the Indian Ocean within the Indonesian Seas, by about 10 million $m^3 s^{-1}$. The Antarctic Circumpolar Current transport passing between Tasmania and Antarctica is estimated as 143 million $m^3 s^{-1}$, with a range from 131 to 158 million $m^3 s^{-1}$.

The Antarctic Circumpolar Current is a deep reaching or barotropic current, meaning that it extends to the seafloor. Because of this it is said that the Antarctic Circumpolar Current 'feels' the shape of the sea floor and hence its path is steered by the seafloor topography (**Figure 4**). The flow following the southern deflection in the mid-ocean ridge reaches its southern-most position in the southwest Pacific Ocean, near 60°S. Upon passing through Drake Passage it turns sharply to the north, transversing the Atlantic Ocean near 50°S. As the ocean surface temperature pattern responds to the circulation pattern the surprising result is that the bottom topography is 'projected' in the sea surface temperature pattern.

Rather than a broad diffuse flow, the Antarctic Circumpolar Current is composed of a number of high speed filaments, separated by zones of low flow, or even reversed flow (towards the west). The jets are typically 40–50 km wide. Surface currents average about 30–40 $cm\,s^{-1}$ within the axes, and speeds of over 100 $cm\,s^{-1}$ are common. The high speed filaments are marked by ocean fronts, where the temperature and salinity stratification changes rapidly with latitude (**Figure 5**). Between these fronts are zones of similar stratification. The primary axis occurs at the polar front (**Figure 6**). Meanders of the flow axes and associated fronts displace these features by at least 100 km to either side of their mean position. Meanders occasionally produce detached eddies, in which pools of water ringed by a high speed current from one zone invade an adjacent zone. A characteristic of the Antarctic Circumpolar Current is its high degree of eddy activity (**Figure 7**). The most active eddy fields are observed where the Antarctic Circumpolar Current crosses submarine ridges or plateaus, as south of Australia, in the southwest Atlantic and south of Africa.

The correlation of the eddy currents and of the ocean temperature leads to significant poleward flux of ocean heat by the eddy processes. The poleward

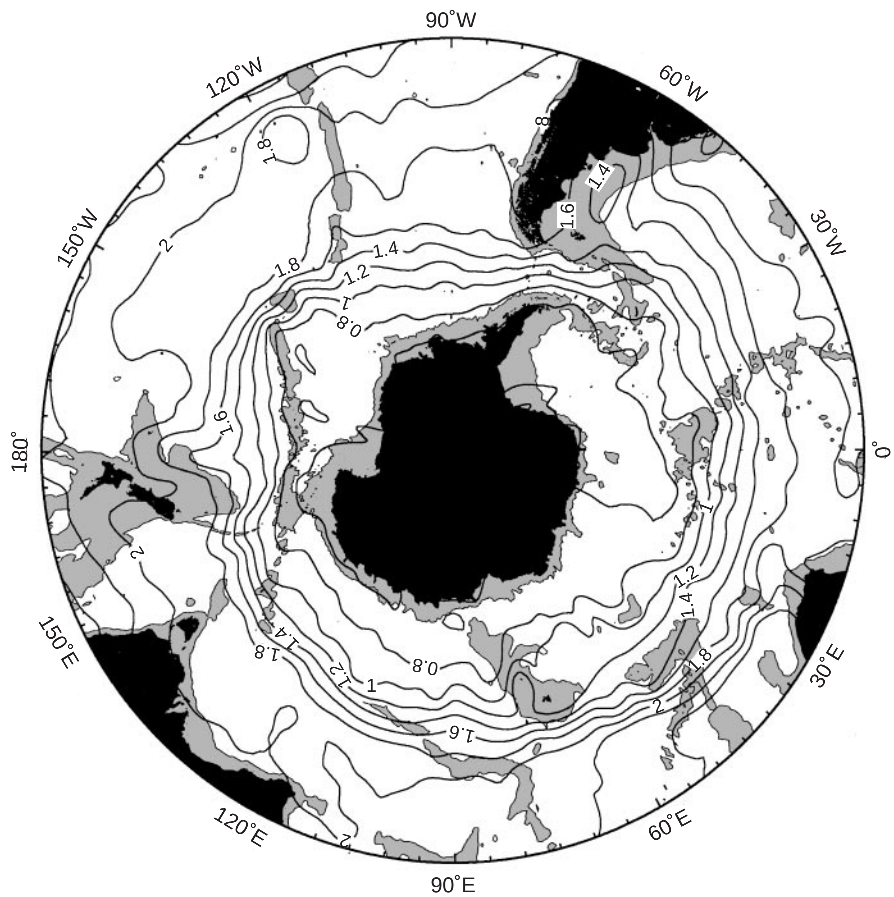

Figure 4 Anomaly of Southern Ocean sea level height relative to the 2×10^7 Pa pressure surface. The values are differences in dynamic meters (approximately equivalent to geometric meters) from that of a standard ocean (0°C, 35 PSU salinity). Land is black; the shaded area marks ocean depths of < 3000 m. Geostrophic ocean currents in the southern hemisphere are directed so that lower sea level is to the right of the flow direction, which is aligned along lines of equal sea level height. The rise of sea level towards the north defines the eastward flowing Antarctic circumpolar current.

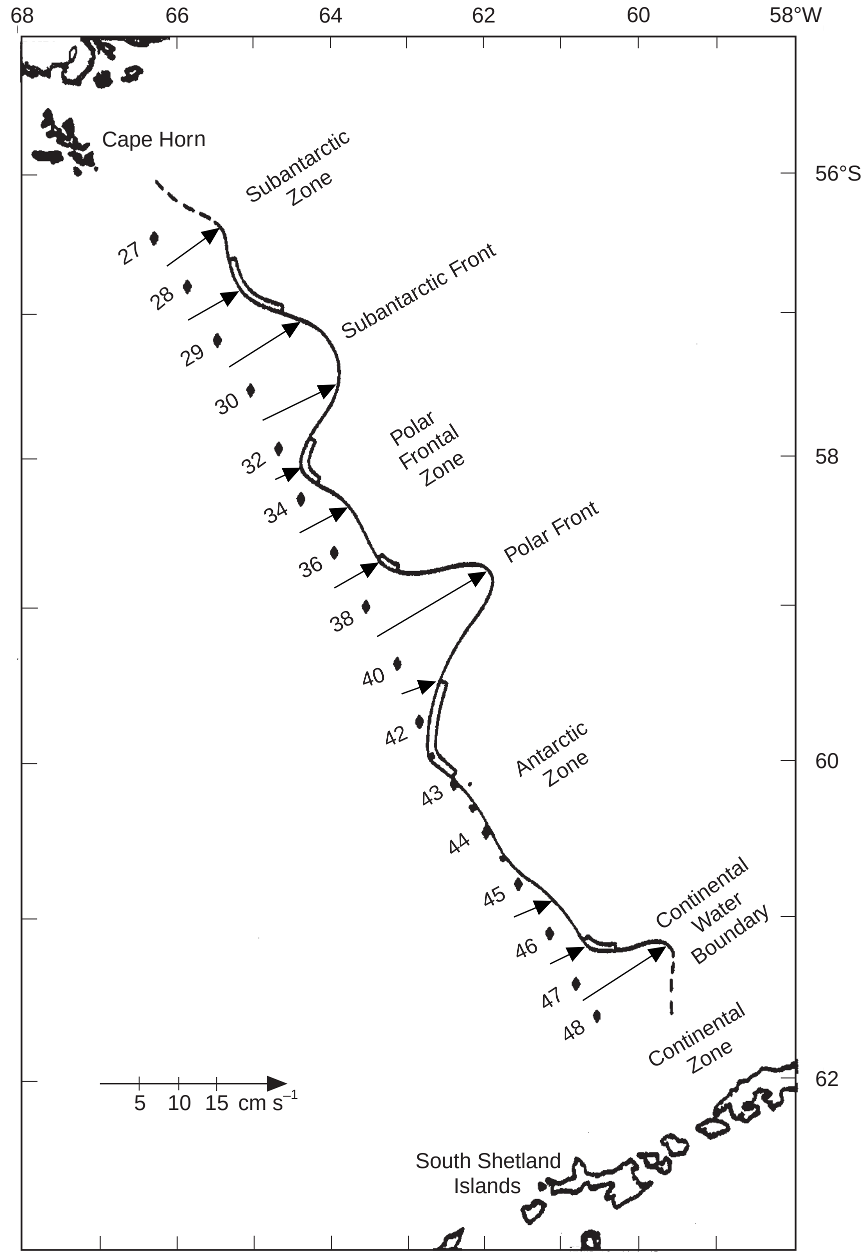

Figure 5 Vertical averaged geostrophic speeds of the upper 2500 m directed normal to a line across the Drake Passage. The positions of the front and stratification zones are shown. The highest flows defining the axes of the Antarctic Circumpolar Current coincide with the position of the ocean fronts. (Reproduced with permission from Clifford, 1983.)

heat flux measured in the Drake Passage, if extrapolated all around Antarctica, is 0.3 PW, which can account for most of the meridional heat flux across 60°S. However caution is suggested as the Drake Passage eddy field may not be typical of the full circumpolar belt. Meanders and eddies of the Antarctic Circumpolar Current also act to carry wind-delivered momentum downward to the seafloor, where pressure forces (often referred to as form drag) acting on the slopes of bottom topographic features act to compensate the force of the wind. The downward transfer of momentum is integrally linked to the meridional fluxes of heat and fresh water by the eddy field, by baroclinic instability.

Weddell Gyre

The Weddell Gyre is the largest of the cyclonic Gyres occupying the region between the Antarctic

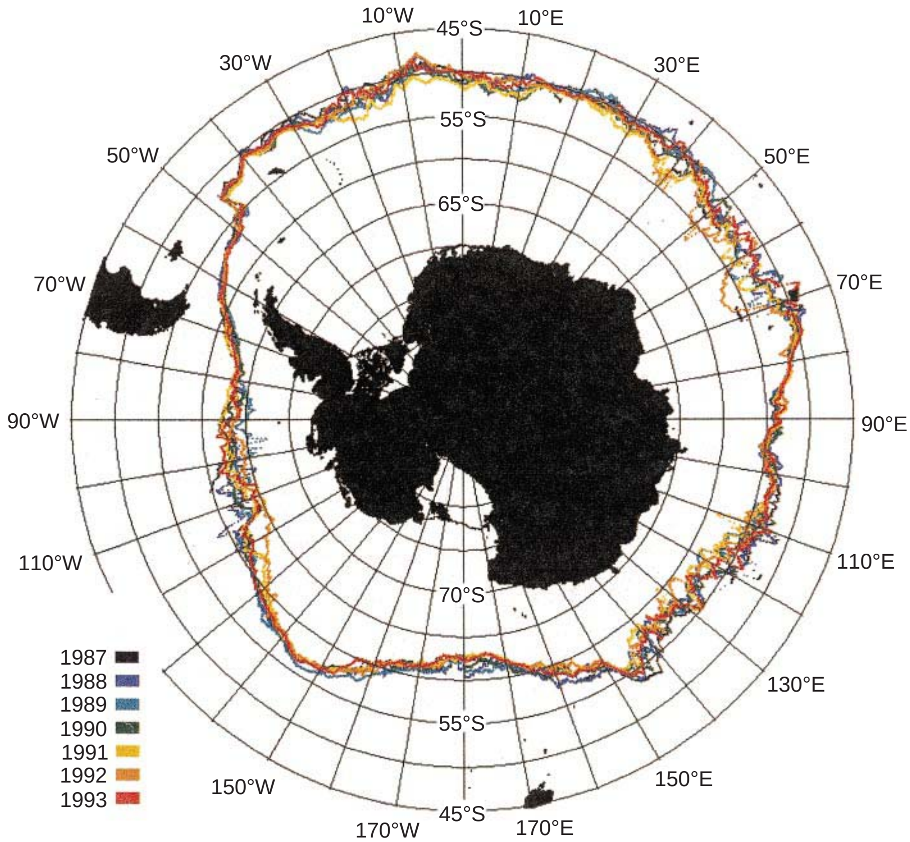

Figure 6 Position of the Antarctic polar front for the years 1987–1993 as revealed by satellite images of sea surface temperature. (Reproduced with permission from Moore *et al*., 1999.)

Circumpolar Current and Antarctica, stretching from the Antarctic Peninsula to 30°E. The clockwise flow pattern is linked to doming of isopycnals and upwelling of deep water within its central axis (Figure 3). As the deep water is warmer than the surface layer the Gyre injects heat into the surface layer, which limits the winter sea ice cover to a thickness of only 0.5 m. Along the Antarctic margins intense cooling of surface water lead to the formation of the coldest, densest ocean water masses of global importance: Antarctic Bottom Water. A branch of the Antarctic Circumpolar Current turns southward near 30°E forming the eastern limb of the Weddell Gyre. Some of this water turns westward along the coast of Antarctica (the rest continues to flow eastward, but at a more southern latitude than the axis of the Antarctic Circumpolar Current). Westward flowing coastal current is characteristic all around Antarctica, with a surface speed of about $10\,\mathrm{cm\,s^{-1}}$ as detected by satellite tracking of the drift of icebergs calved from Antarctica.

Within the Weddell Gyre the coastal current westward flow is blocked by the Antarctic Peninsula. Upon encountering the southern base of the peninsula, the coastal current turns northward, forming the western boundary current of the Weddell Gyre. At the northern tip of the Antarctic Peninsula, the western boundary current composed of the cold, low salinity stratification characteristic of Antarctic continental margin, is injected into the open ocean. This feature, called the Weddell-Scotia Confluence (**Figure 2**) separates the Antarctic Circumpolar Current from the interior of the Weddell Gyre. It can be traced as a low salinity band to the Greenwich Meridian. Along the sea floor Antarctic Bottom Water escapes from the Gyre, flowing northward within deep crevices in the seafloor morphology, into the Scotia Sea, South Sandwich Trench and south of Africa. Export of Bottom Water is compensated by import of circumpolar water along the eastern boundary.

Surface currents of the Weddell Gyre are weak, usually $10\,\mathrm{cm\,s^{-1}}$, but the flow extends to the seafloor, as a strongly barotropic current. There is some evidence that the current increases along the seafloor of the continental slope, with speeds of up to $20\,\mathrm{cm\,s^{-1}}$, associated with plumes of dense shelf water descending into the deep ocean as Antarctic

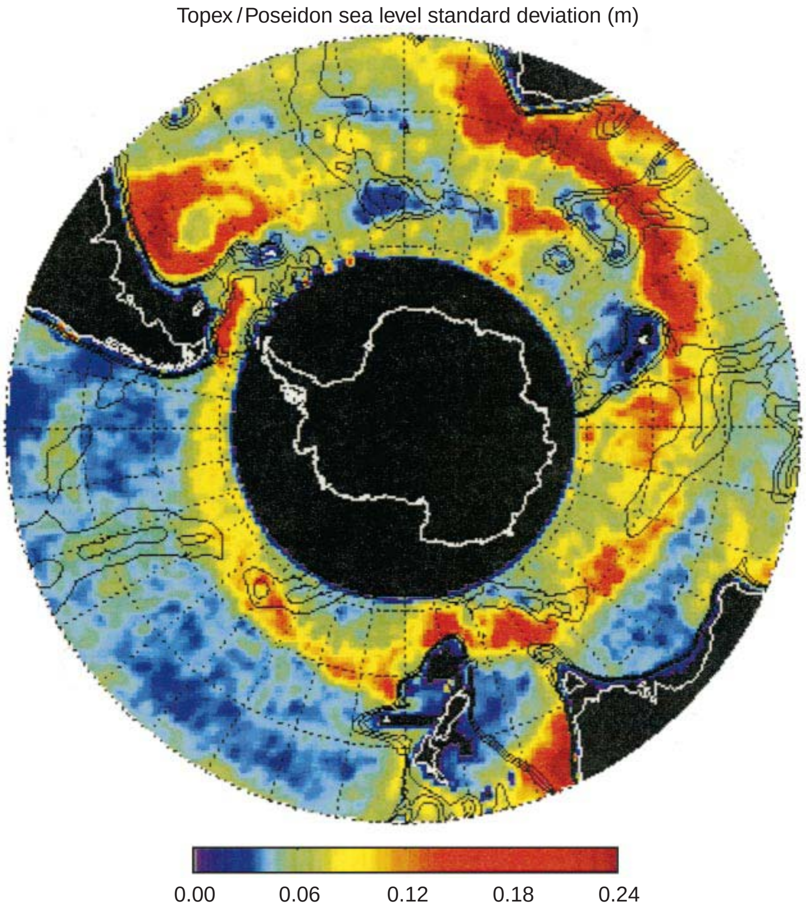

Figure 7 Variability of sea surface height from mean sea level, as revealed by Topex Poseidon satellite altimetric measurements of sea level for the period 1992–1999. Values are in meters. Variability of sea level is caused by meanders and eddies of the geostrophic flow field, or changes in its strength. (Provided by Donna Witter, Associated Research Scientist at Lamont-Doherty Earth Observatory.)

Bottom Water. Observations of ocean currents during the period from 1989 to 1992 across the mouth of the Weddell Sea, stretching from Kapp Norvegia (71°20′S; 11°40′W) to the northern tip of the Antarctic Peninsula, find Gyre transport of about 30 million $m^3 s^{-1}$ (30 Sv), most of which is contained in narrow jets following along the continental slope. An additional 10 million $m^3 s^{-1}$ (10 Sv) of transport is likely around the central axis of the Gyre, making a total recirculation transport around the Gyre of 40 million $m^3 s^{-1}$ (40 Sv). Export from the Gyre is not known exactly, but can be estimated as 5 million $m^3 s^{-1}$ (5 Sv) within the bottom layer.

See also

Agulhas Current. Antarctic Circumpolar Current. Atlantic Ocean Equatorial Currents. Icebergs. Indian Ocean Equatorial Currents. Indonesian Throughflow and Leeuwin Current.

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