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Abstract: The Southern Ocean contains a large, wind-driven current, the Antarctic Circumpolar Current, which carries approximately 170×10^6 m^3 of water eastward around Antarctica within multiple filamented jets. To the south of the Antarctic Circumpolar Current, within the Antarctic marginal seas, the Weddell Gyre transports water cyclonically (clockwise) around the Weddell Sea, and the Ross Gyre transports water

cyclonically around the Ross Sea. Southward flow at mid-depth in the Southern Ocean is returned northward at the surface, as Ekman transport, or at depth, as part of bottom water export.

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Summary

The Southern Ocean, encircling Antarctica, plays a major role in shaping the characteristics of the global ocean. Its major currents serve as conduits linking the three major ocean basins: the Atlantic, Pacific and Indian. The most prominent current is the Antarctic Circumpolar Current, which consists of multiple filaments that together transfer about 170 million $m^3 s^{-1}$ of sea water from west to east within a latitudinal range from 45 ° to 65°S. North of the Antarctic Circumpolar Current are the Subtropical Fronts, the poleward limbs of the large subtropical gyres of the southern hemisphere, sometimes referred to as the South Atlantic, South Indian, and South Pacific Currents. South of the Antarctic Circumpolar Current, within large embayments of Antarctica, notably the Weddell and Ross Seas, are large clockwise flowing gyres. The Weddell Gyre carries about 40 million $m^3 s^{-1}$ of water and the Ross Gyre about 20 million $m^3 s^{-1}$. Along the Antarctic continental shelf is a coastal current, the Antarctic Slope Current, which advects water from east to west.

Besides its surface-intensified eastward or westward flowing ocean currents, the Southern Ocean experiences major overturning of ocean water, with water moving

southward along density surfaces at mid-depth and returning northward at the surface or at the bottom (e.g. Meredith et al, 2011). Overturning is forced in part by the production of dense surface water along the margins of Antarctica, leading to the formation of Antarctic Bottom Water. Northward surface flow is part of a wind-driven Ekman transport, but northward flow can be more intensified in certain locations. For example, along the east coast of the Antarctic Peninsula, the Antarctic Slope Current forms the western boundary of the Weddell Gyre. 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 largely driven by the wind, which exerts a stress on the sea surface. The winds are strong over the Southern Ocean, particular within the Indian Ocean and Australian sectors (Figure 1) and therefore drive a vigorous circulation (e.g. Nowlin and Klinck, 1986) (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.

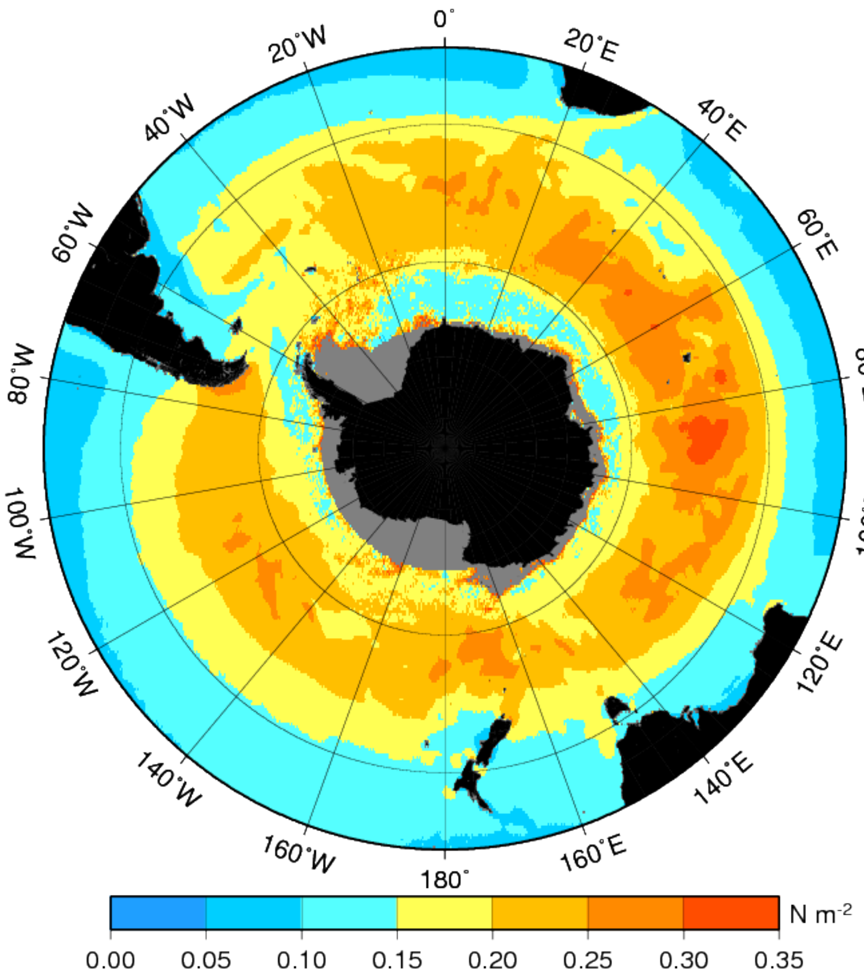


Figure 1. Average magnitude of wind stress in N m^{-2}. Wind stresses are computed from measurements by the QuikSCAT satellite and have been averaged over 10 years (from September 1999 through August 2009). Wind direction is not shown in this map of wind-stress magnitude. Data are released by NOAA NESDIS CoastWatch (https://catalog.data.gov/dataset?tags=wind+stress).

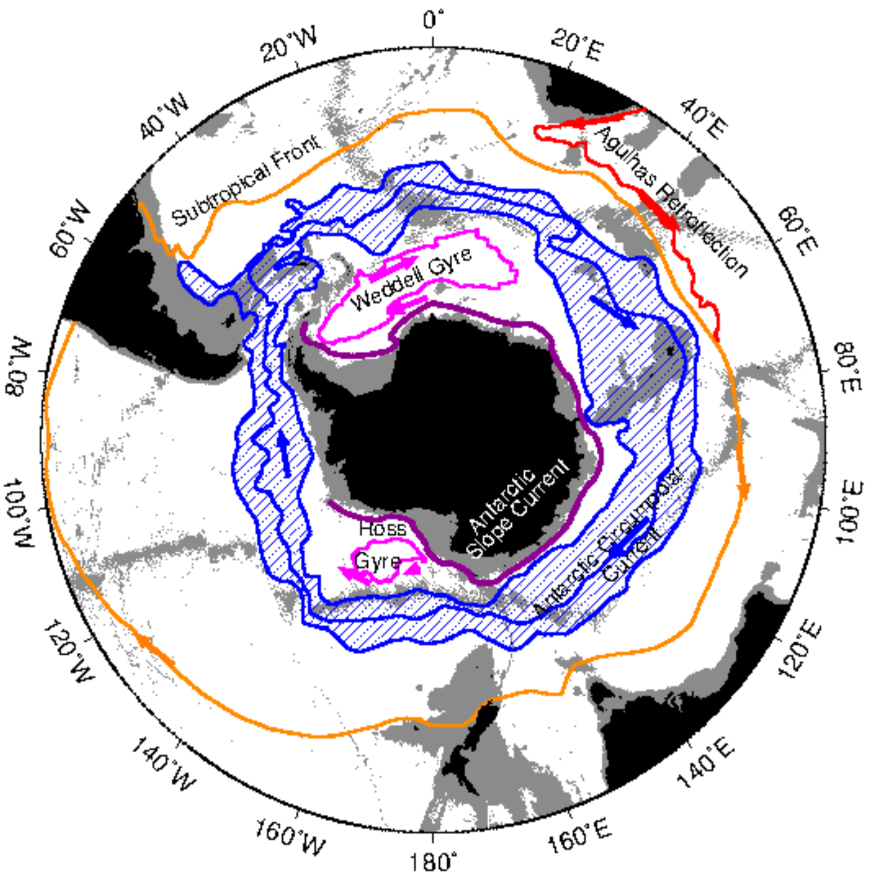
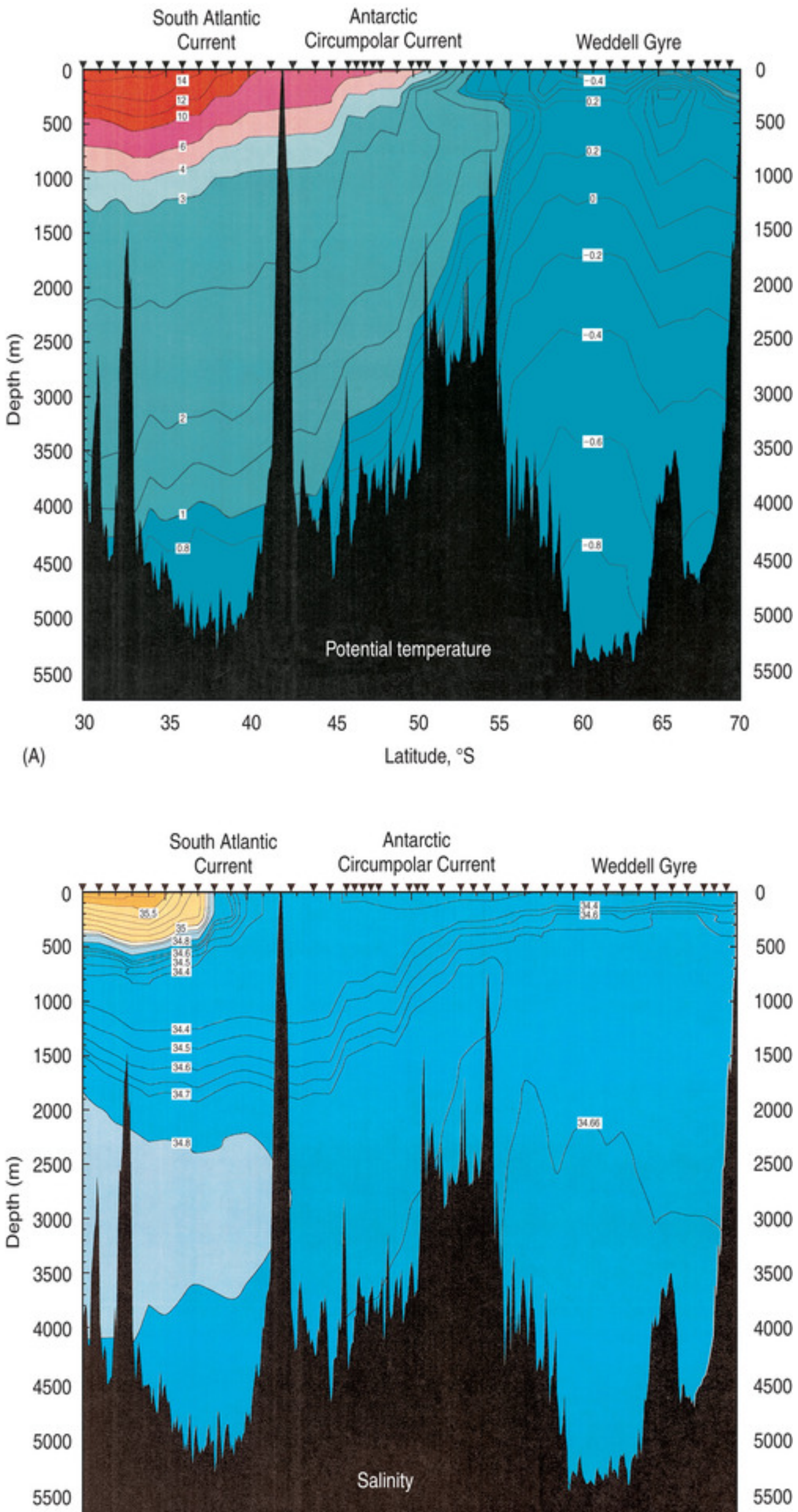


Figure 2. Schematic of general circulation of the Southern Ocean. The broad location of the Antarctic Circumpolar Current (blue shading) is roughly bounded by the Southern Antarctic Circumpolar Current Front to the Southern and by the Subantarctic Front to the north, with the Polar Front in between (all three fronts indicated by blue lines). The Subtropical Front (orange) roughly marks the transition between the subtropical gyres in each ocean basin and the Southern Ocean circulation. The westward flowing Antarctic Slope Current (dark purple) is most clearly defined from 120°W to 55°W (Chavanne et al, 2010, Armitage et al, 2018). Land is black; the shaded area marks ocean depths of <3000 m, arrows indicate prevailing flow directions.

Ocean currents are for the most part in equilibrium with oceanic density, approximately satisfying the so-called ‘thermal wind equation’ or `geostrophic balance’. The thermal wind equation implies that strong currents align with fronts, which are regions of rapidly changing temperature, salinity, and density, Throughout the Southern Ocean surfaces of constant density, known as isopycnals rise up toward the sea surface as latitude increases to the south. This can be illustrated, for example, along the Greenwich meridian (Figure 3). Thus at any given depth, there is a north-south gradient in both density, and correspondingly pressure, that can sustain a geostrophically balanced current. 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 toward the west.

The density gradients that identify the positions of strong geostrophic currents are directly linked to the wind in the Southern Ocean. Because of the Earth's rotation, the Southern Ocean's westerly winds push surface water northward as `Ekman transport'. This establishes higher pressure (and lower density) to the north, maintaining the gradients that support the eastward flowing geostrophic current.

Buoyancy changes of surface water induced by air-sea fluxes of heat and fresh water, often involving sea ice within the Southern Ocean, also produce circulation. Oceanic circulation that is directly driven by buoyancy (often referred to as the Meridional Overturning Circulation) is mainly oriented in the north-south direction and is sluggish compared with the directly wind-driven circulation. Sinking of dense waters along the continental margins of Antarctica results in Antarctic Bottom Water. This sinking induces a compensatory upwelling of less dense resident water, which rises along equal density surfaces known as isocpycnals. .


South Atlantic Current
Antarctic Circumpolar Current
Weddell Gyre
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
14
12
10
6
4
3
2
1
0.8
−0.4
0.2
0.2
0
−0.2
−0.4
−0.6
−0.8
Potential temperature
30
35
40
45
50
55
60
65
70
(A)
Latitude, °S
South Atlantic Current
Antarctic Circumpolar Current
Weddell Gyre
Depth (m)
35.5
35
34.8
34.6
34.5
34.4
34.4
34.5
34.6
34.7
34.8
34.4
34.6
34.66
Salinity

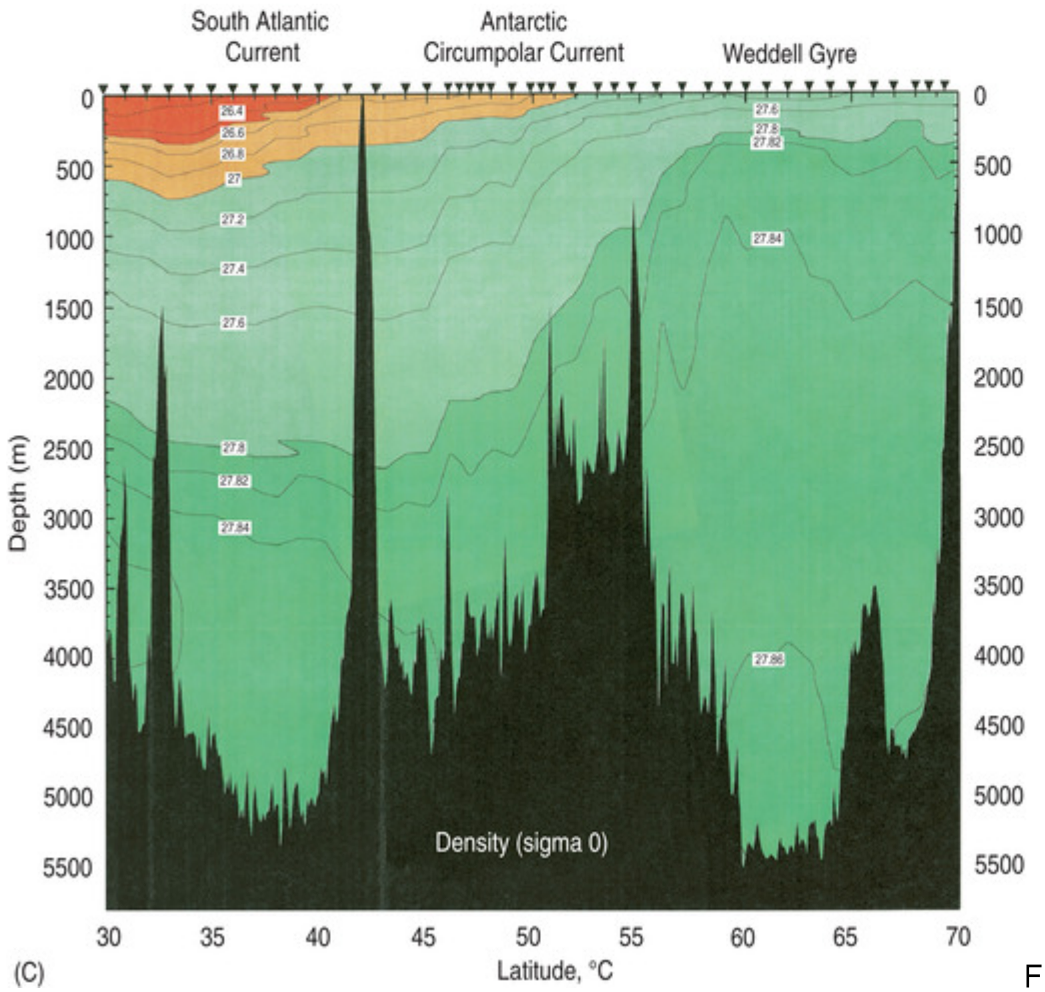


Figure 3. Potential (A) temperature, (B) salinity, and (C) density (sigma-0) along the Greenwich meridian.

The strength of the wind varies with latitude (Figure 1). Maximum westerlies in the wind occur near 55°S, which roughly coincides with the central core of the Antarctic Circumpolar Current. To the south of this latitude, the meridional gradient in wind-induced northward Ekman transport of surface water results in a wide region of upwelling. North of 55°S, weaker winds imply a weaker Ekman transport. This causes a region of surface water convergence. At the northern boundary of the Antarctic Circumpolar Current, north of about 55°S surface water is able to sink under the more buoyant surface water, 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 helps to sustain two large clock-wise-flowing, cyclonic gyres within the large embayments of Antarctica, marking the Weddell and Ross Seas (Figure 2).

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 45° to 65°S. It transports more water and extends over a longer distance than any other ocean current system on Earth, covering a distance of 21 000 km, with the average transport through the Drake Passage (between South America and the Antarctic Peninsula) estimated at 173 million $m^3 s^{-1}$ (173 Sv) (Donohue et al, 2016). The transport varies with time by at least ±10 million $m^3 s^{-1}$, mirroring variations in the circumpolar wind field. The Antarctic Circumpolar Current transport south of Australia is enhanced by about 15 million $m^3 s^{-1}$; the extra flow recirculates around the northern side of Australia as the Indonesian Throughflow.

The Antarctic Circumpolar Current is a deep reaching current, sometimes referred to as “equivalent barotropic”, meaning that it is surface intensified but extends to the seafloor (Gordon et al, 1978). Because of this, the Antarctic Circumpolar Current’s path is steered by the seafloor topography (Figure 4) around plateaus and through openings in the mid-ocean ridges. It reaches its southern-most position in the southwest Pacific Ocean, near 60°S (e.g. Mazloff et al, 2010). Upon passing through Drake Passage it turns sharply to the north, traversing the Atlantic Ocean at a latitude near 45-50°S.

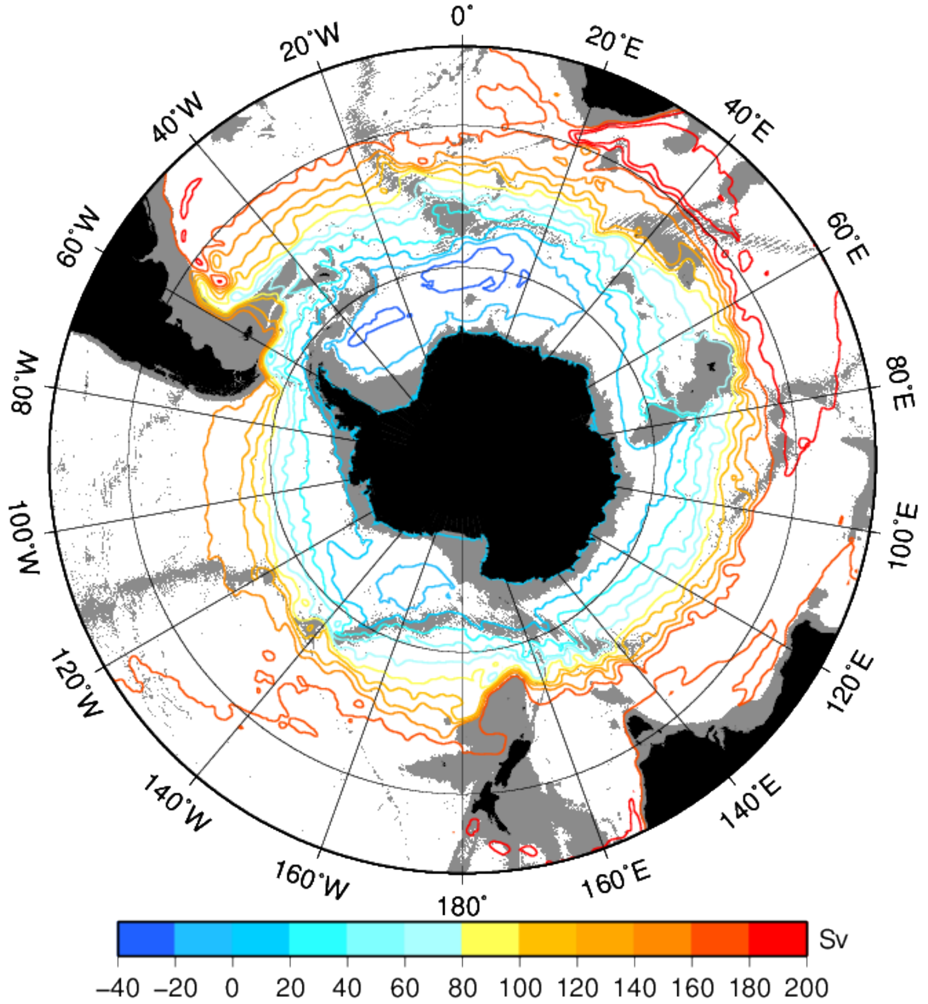


Figure 4. Geostrophic transport streamlines in the Southern Ocean from an assimilating ocean model, the Southern Ocean State Estimate. The values are in units of million m, referred to as Sverdrups (Sv). Land is black; the shaded area marks ocean depths of <3000 m. Geostrophic ocean currents in the southern hemisphere are directed so that lower streamlines are to the right of the flow direction, which is aligned with the transport streamlines. (SOSE developed by Mazloff et al, 2010. Data from sose.ucsd.edu)

Rather than being a broad diffuse flow, the Antarctic Circumpolar Current is composed of a number of high speed filament-like jets (Orsi et al, 1995; Sokolov and Rintoul, 2009). Each of these jets is in geostrophic balance, meaning that each strong current filament coincides with an oceanic front, where temperature and salinity change rapidly with latitude (Figure 5). From north to south, the primary fronts are identified as the Subantarctic Front, the Polar Front, and the Southern ACC Front (blue lines in Figure 2). In Drake Passage the jets vary in width between 75 km (for the Southern ACC Front) to 200 km (for the Polar Front). .. Most of the transport is carried by the Subantarctic Front and the Polar Front, and surface currents average about 30–40 cm s^{-1} within the Subantarctic and Polar Fronts (e.g. Firing et al, 2011). Jets are separated by zones of low flow, or even reversed flow (towards the west) and comparatively homogeneous water properties.

The fronts are highly variable: each of the fronts can have multiple quasi-stable positions (e.g. for the Polar Front, a northern, central and southern expression) that strengthen and weaken over time (Sokolov and Rintoul, 2009). In addition, the frontal positions can meander northward and southward in time. This results in meridional displacements of each front by ±100 km to either side of their mean positions (Gille and Kelly, 1996; Sokolov and Rintoul, 2009). The Polar Front coincides with a distinct transition in surface temperature and thus its mean and time varying position can be mapped from satellite sea surface temperature (Freeman and Lovenduski, 2014) (Figure 6). 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. Meanders also occasionally produce detached eddies, in which pools of water ringed by a high speed current from one zone invade an adjacent zone.

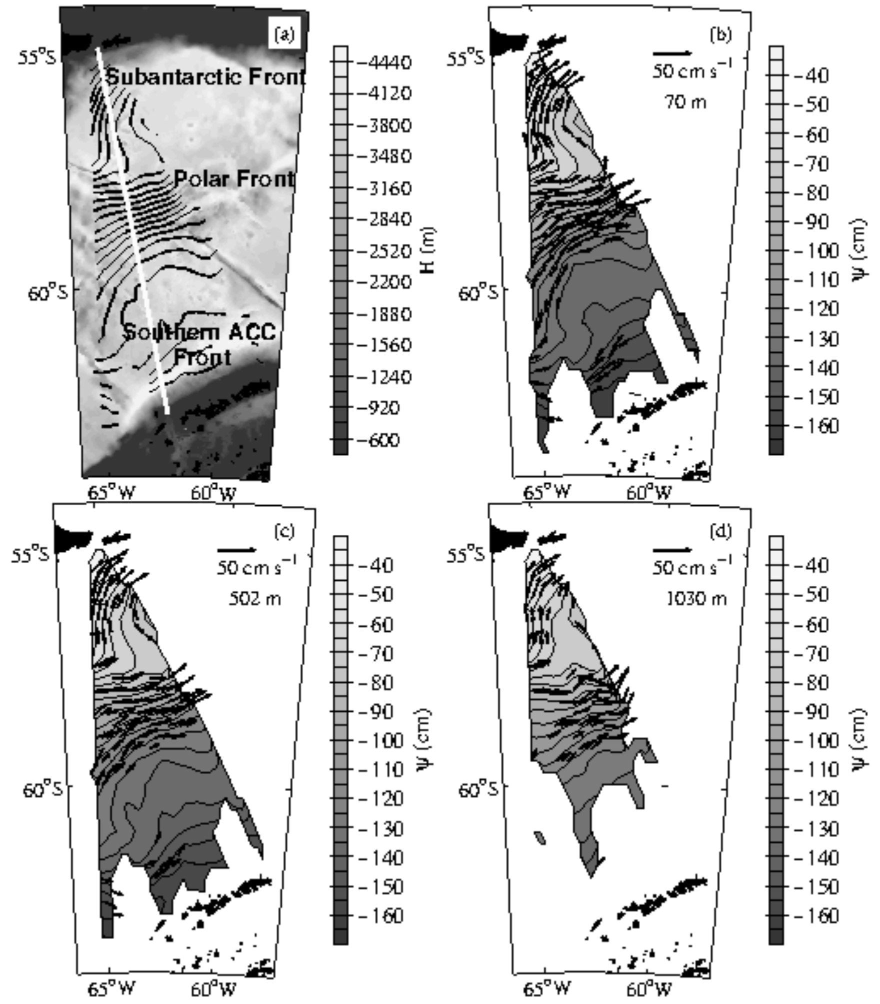


Figure 5. Stream function ψ in the Drake Passage region between South American and the Antarctic Peninsula, objectively mapped from Acoustic Doppler Current Profiler data, and contoured at 5 cm intervals: (a) depth-mean stream function overlaid on bathymetry H, with the most commonly sampled line in white, and (b–d) stream function and current vectors at several depths, with only currents larger than 15 cm s^{-1} plotted. (Adapted and reproduced with permission from Firing et al, 2011)

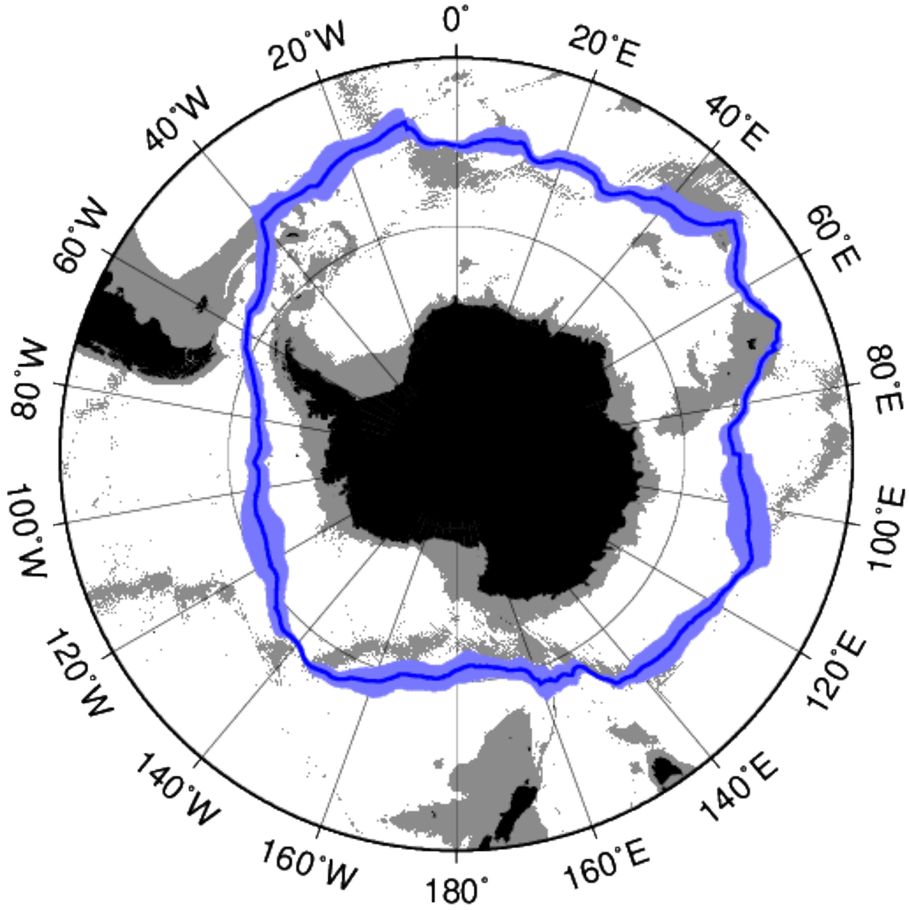


Figure 6. Mean position of the Antarctic Polar Front for the years 2002-2014 as inferred from microwave satellite images of sea surface temperature. Blue shading indicates one-standard deviation range, indicating the range of most of the temporal variability. Frontal analysis by Freeman and Lovenduski (2016).

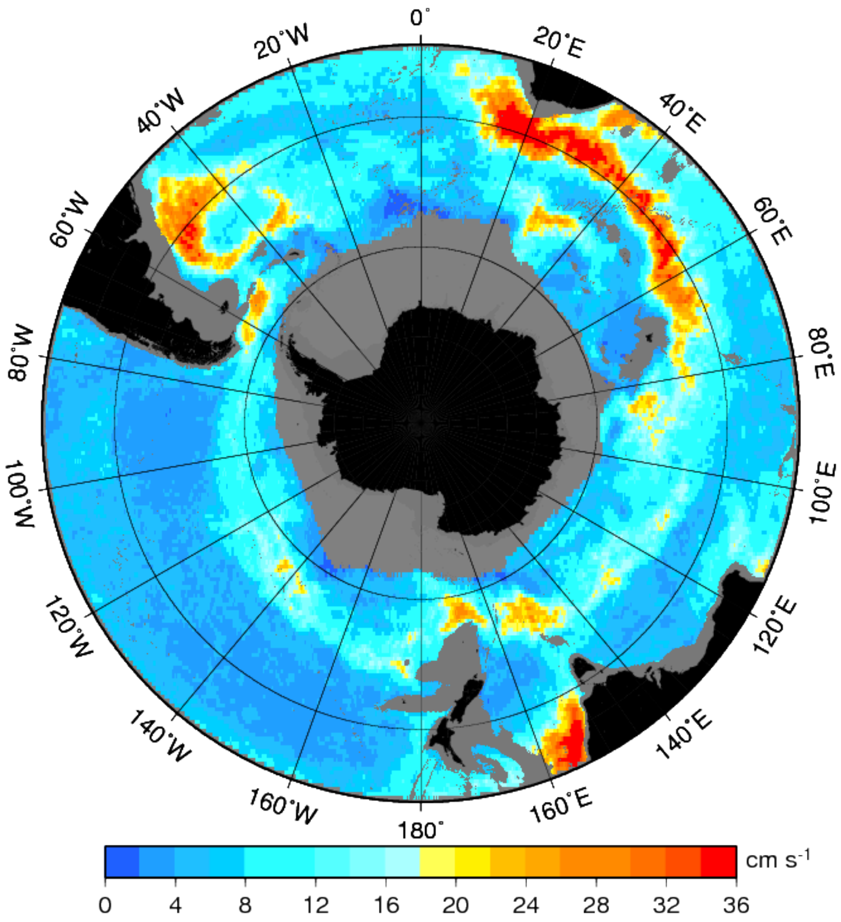


Figure 7. Variability of surface current speed, computed from the standard deviation of geostrophic velocity determined from satellite measurements of sea surface height, from the Aviso gridded sea surface height product Variability in velocity is caused by eddies and meandering of the flow and changes in current strength   Areas shallower than 2000 m are shaded gray. (Computed from AVISO altimetry.)

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 heat flux measured in the Drake Passage, if extrapolated all around Antarctica, is sufficient to account for 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 Circumpolar Current and Antarctica. It stretches from the Antarctic Peninsula to 30°E. Its clockwise flow pattern is wind driven (e.g. Armitage et al, 2018) linked to doming of isopycnals and upwelling of deep water near its center (Figure 3). South of the Polar Front, the ocean is cold enough that density is determined by salinity rather than temperature. In the Weddell Gyre, this means that dense, deep water is warmer than surface water, and upwelling can bring warm water into the surface layer. This limits the winter sea ice cover to a thickness of only 0.5 m, and in some years an open water ice-free polynya can occur in the center of the Weddell Gyre. Along the Antarctic margins intense cooling of surface water leads to the formation of the coldest, densest ocean water masses of global importance: Antarctic Bottom Water. The eastern limb of the Weddell Gyre flows southward near 30°E. It turns westward along the coast of Antarctica. A westward flowing coastal current is characteristic all around Antarctica, with a surface speed of about 10 cm s^{-1} as detected by satellite tracking of the drift of icebergs calved from Antarctica.

Within the Weddell Gyre, the coastal current follows the Antarctic Peninsula northward, forming the western boundary current of the Weddell Gyre (Thompson and Heywood, 2008). 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 Weddell Gyre, flowing northward within deep passageways 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 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 cm s^{-1}, associated with plumes of dense shelf water descending into the deep ocean as Antarctic Bottom Water. Observations along the western boundary of the Weddell Sea at the northern tip of the Antarctic Peninsula suggest a total gyre transport of 40-50 million m^3 s^{-1} (40-50 Sv), most of which is contained in narrow jets following along the continental slope (Thompson and Heywood, 2008). Export from the Weddell Gyre has been estimated to include about 7 million m^3 s^{-1} (7 Sv) of water from the Antarctic Shelf Current (Heywood et al, 2004; Meijers et al, 2016).

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Original article (and 2nd edition revision) by Arnold Gordon

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