The same populations are hunted more heavily off Newfoundland and Labrador in winter, with the annual kill estimated at about 200 000 since 1993. Although it is only legal to kill murres, some razorbills and dovekies, and a few puffins, are also shot.

Although direct harvests have affected several auk species and were responsible for the extermination of the great auk, the effects of mammalian predators, introduced either deliberately, or accidentally, have probably had a much greater impact on auk populations worldwide. The main agents of destruction were foxes, introduced throughout the Alaskan islands for fur farming. Rats have also caused many declines and extirpations. Raccoons and mink have an important impact in some areas, and rabbits, through their effects on vegetation and soil, may also have caused problems for some burrowing species.

Japanese, Craveri's, Xantus' and marbled murrelets are all considered endangered or threatened in one way or another. It is certain that the majority of auk populations are smaller, in many cases much smaller, than they would have been a few centuries ago. Probably, we will see little change in that situation, although programs to eliminate introduced predators from certain important Pacific islands may improve the situation for some species. All auks are very susceptible to contamination by oil and they have formed the majority of seabirds killed in oil spills off Europe and North America. Unlike gulls, they have not profited at all from fisheries wastes. Protection from egging has led to increases of some species in the twentieth century. However, overall, the auks remain precariously dependent on human goodwill for their future survival.

See also

Fish Predation and Mortality. Laridae, Sternidae and Rynchopidae. Network Analysis of Food Webs. Plankton. Seabird Conservation. Seabird Foraging Ecology. Seabird Migration. Seabird Population Dynamics. Seabirds and Fisheries Interactions. Seabirds as Indicators of Ocean Pollution.

Further Reading

Gaston AJ and Jones IL (1998) *The Auks: Family Alcidae.* Oxford: Oxford University Press.

Birkhead TR and Nettleship DN (1985) *The Atlantic Acidae.* London: Academic Press.

Harris MP (1989) *The Puffin.* London: T & AD Poyser.

Gaston AJ and Elliot RD (eds) (1991) *Conservation Biology of the Thick-billed Murre in the Northwest Atlantic.* Ottawa: Canadian Wildlife Service.

Sealy SG (ed.) (1990) *Auks at Sea.* Studies in Avian Biology 14, Cooper Ornithological Society.

Friesen VL, Baker AJ and Piatt JF (1996) Phylogenetic relationships within the Alcidae (Aves: Charadriiformes) inferred from total molecular evidence. *Molecular Biology and Evolution* 13: 359–367.

ANTARCTIC CIRCUMPOLAR CURRENT

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doi:10.1006/rwos.2001.0370

The Antarctic Circumpolar Current (ACC) flows eastward around the globe in the Southern Ocean, driven by the strong eastward winds characteristic of southern polar latitudes. Direct and indirect measurements of the total transport of this current are consistent with the idea that average winds drive the average flow. However, abrupt changes in transport do not correspond to changes in local winds, nor do changes occur consistently around the globe. The path of the ACC is controlled by ocean depth through the tendency for large-scale ocean flow to be along lines of constant planetary vorticity (Coriolis parameter divided by depth). Drake Passage is the narrowest constriction to this flow (about 700 km in width). Strong current extends throughout the water column related to an upward tilt of the constant density, temperature, and salinity surfaces to the south. The strongly tilted property surfaces in the ACC allow deep (3–4 km deep) water, originating in the polar North Atlantic, to reach the surface where it is driven northward by the winds, thus completing the circuit. The ACC is composed of three circumpolar, frontal jets, each having about three times the speed of the flow between the fronts. Dynamic instability

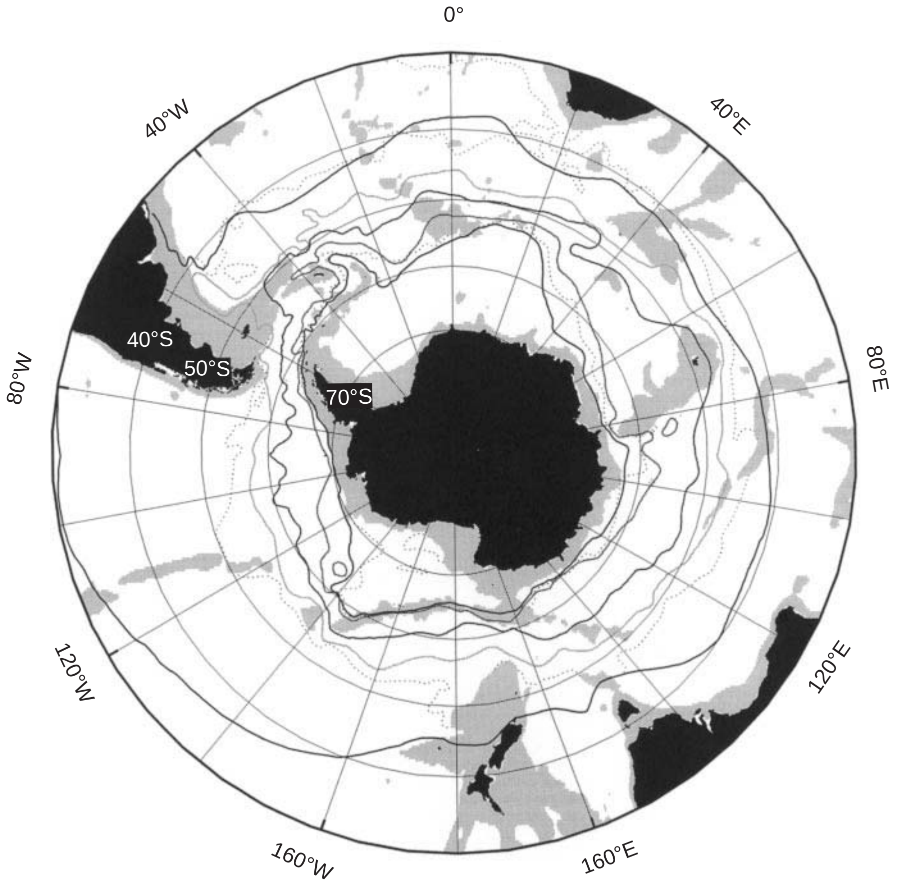

Figure 1 Polar view of Southern Ocean with climatological locations of circumpolar fronts. From north to south, these fronts are Subtropical Front, Subantarctic Front, Polar Front, and Southern ACC Front. The southern boundary of the ACC also is shown. Black outlines show land. Gray shading indicates regions where water is shallower than 3000 m. (Courtesy of Alex Orsi.)

of these jets creates eddies (about 150 km in diameter) which redistribute momentum and water properties.

Introduction

The Southern Ocean, that part of the global ocean covering the higher latitudes of the southern hemisphere, is unique in being continuous around the globe. This allows exchange of mass, heat, fresh water, carbon, and other properties, including living material, among the three major oceans: Atlantic, Indian, and Pacific.

The specific boundary between the Southern Ocean and the rest of the global ocean depends on characteristics of the water, not land boundaries. The northern edge of the Southern Ocean is marked by the Subtropical Front (**Figure 1**), where water near the surface changes from warm and salty (12°C, 35.0; characteristic of lower latitudes) to cold and fresh (10°C, 34.6; characteristic of polar latitudes). The southern edge of the Southern Ocean is marked by Antarctica.

Within the Southern Ocean is a large eastward flowing current, the Antarctic Circumpolar Current (ACC), which flows unbroken around the globe. The narrowest constriction to this flow is Drake Passage (about 700 km across) at the southern tip of South America. By convention, any flow through this passage is part of the ACC. The eastward flow associated with the Subantarctic Front marks the northern boundary of the ACC. The southern boundary of the ACC is less dramatic, being recently defined (middle 1990s) based on water properties (specifically, the surfacing of water originating in the north Atlantic). South of the southern boundary of the ACC are polar gyres filling the Weddell and Ross seas, which are not part of the ACC.

Drake Passage opened about 30 million years ago as South America and Antarctica separated allowing the ACC to form. This current formation is thought to have a profound influence on Antarctica and global climate as there was a simultaneous accumulation of ice over Antarctica and a global decline in sea level. The ACC also isolated Antarctica biologically allowing a unique marine ecosystem to evolve.

An early numerical model study of the dynamical effect of Drake Passage found that as the Passage deepened export of dense Antarctic water declined and the speed of the ACC increased. A more recent study using a more realistic global ocean model confirmed these influences of an open passage, and showed that reduced outflow of Antarctic dense water increased deep-water formation in the North Atlantic.

The ACC was discovered by European mariners in the late seventeenth century with the first reported crossing by Edmond Halley on the HMS *Paramore* (1699–1700). After this time, a number of mariners explored this region for the purposes of commerce and science. Notable explorers were James Cook (1772–1775), Thaddeus Bellingshausen (1819–1821), and James Clark Ross (1839–1843). Many unnamed sailors came looking for seals and whales and so kept their knowledge secret. The late nineteenth and early twentieth centuries saw an explosion of oceanographic research by various countries which constituted the first large-scale survey of the Southern Ocean, providing measurements of water properties and current speeds in the ACC.

Large-Scale Structure

The ACC is 23 000 km long (at 55°S) and up to 2000 km wide (about 20° of latitude) in some regions away from Drake Passage (**Figure 1**). The general eastward flow of the ACC is strongest near the surface with speeds between 0.25 and 0.4 m s^{-1}. Unlike lower latitude currents, such as the Gulf Stream, ACC currents extend throughout the water column, declining monotonically with depth to a few centimeters per second near the bottom (2.5 km or greater). Transport of water by the ACC is 100–150 $\times 10^6\,\mathrm{m^3\,s^{-1}}$, several times larger than other strong currents in the ocean (such as the Gulf Stream or Kuroshio).

Distributions of potential temperature, salinity, and density across the ACC (**Figure 2**) reveal the characteristic southward upward tilt of surfaces on which property values are nearly uniform. The tilt is so strong that the salinity maximum and the 2°C isotherm found 3 km deep on the north side of the ACC are within a few hundred meters of the surface on the south side. This tilt is a consequence of the flow dynamics and is a reason for the importance of the ACC in global transport of heat and other properties. Tilting density surfaces create horizontal pressure changes which, coupled with the Coriolis force, drive the eastward flow in the ACC. More specifically, the north to south increase in density at

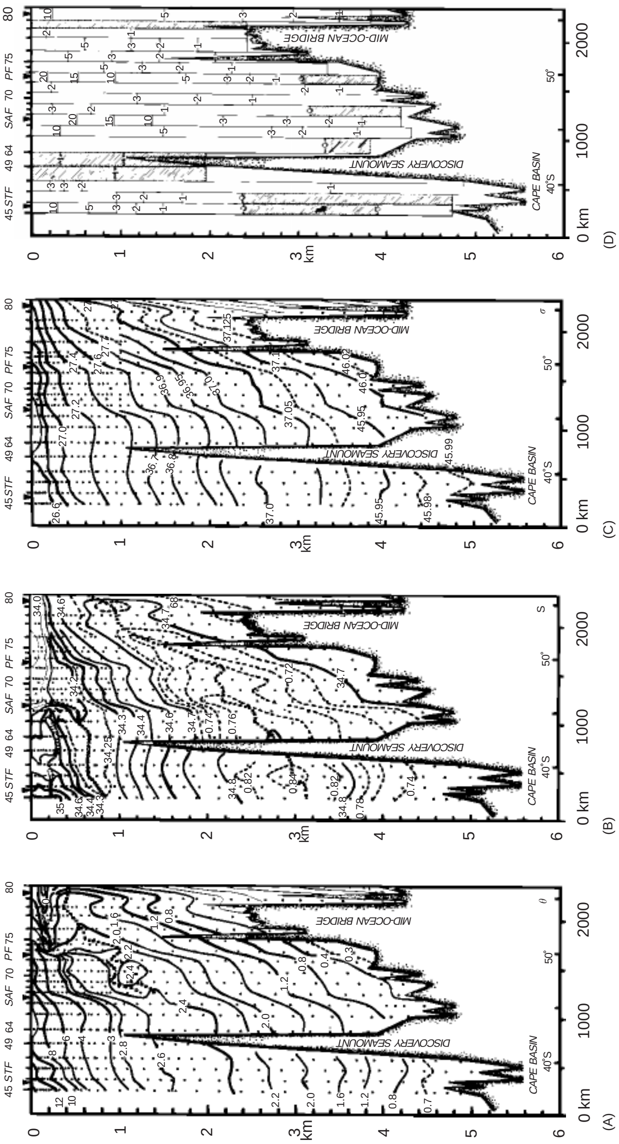

Figure 2 Sections of temperature, salinity, density, and geostrophic flow relative to 3000 m across the ACC along the Greenwich Meridian. On each figure x or o indicate maxima or minima of a property: (A) potential temperature (°C); (B) salinity; (C) potential density; and (D) geostrophic flow (cm s^{-1}) assuming zero flow at the deepest depth for each station pair. Shaded columns are westward flow. (Modified from Whitworth and Nowlin, 1987.)

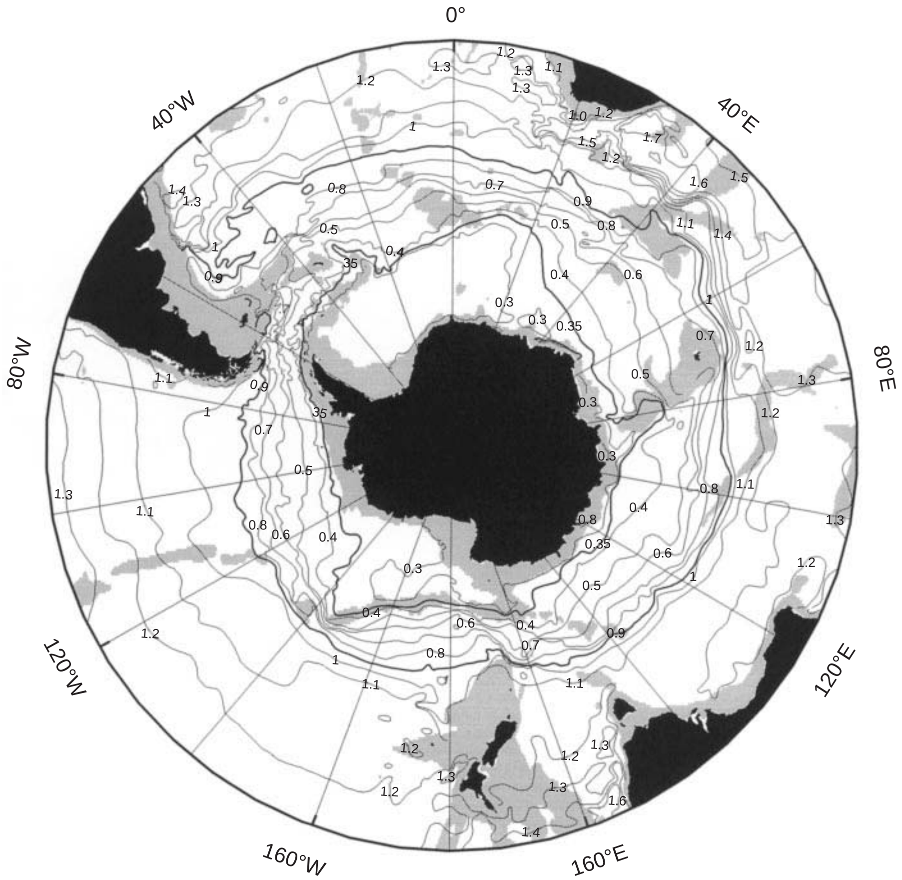

Figure 3 Dynamic topography of the 50-m depth surface relative to 1000 m. The surface slope, with the choice on no pressure gradient at 1000 m, is estimated from measurements of water density. Curves represent contours of equal surface height (m) and approximate the streamlines of surface currents. Black outlines show land. Gray shading indicates areas with depths less than 3000 m. (Courtesy of Alex Orsi.)

every depth (**Figure 2C**) produces a vertical change in the flow, which is slower with depth, that is responsible for the monotonic decline in the speed of the ACC with depth (**Figure 2D**).

ACC flow obtained from density changes by geostrophic estimates, with the choice of no flow near the bottom, compares well to direct current measurements in Drake Passage as well as to surface flow speed measured by surface drifters. This good comparison validates the estimates of the slope of the ocean surface (**Figure 3**) based on all density observations. From these estimates, as well as flow estimates from surface drifters and the surface slope measured from satellites, it is clear that the ACC flows continuously around the Southern Ocean.

The basic force balance for the ACC was first identified in the middle of the twentieth century. Wind stress accelerates the water near the surface and form drag (pressure acting on bottom depth variations) retards the deep flow. Alternative force balances that balance the wind with friction (either bottom friction or horizontal friction against the continental margins) are not plausible due to the enormous level of turbulence that would be required to provide the retarding force. Such turbulence would not allow the observed water properties to exist.

The force balance in the ACC is different from that in the rest of the ocean, which is also driven largely by surface wind stress. In most of the ocean, arge-scale pressure gradients, due to land boundaries, balance the effect of the wind stress. In the Southern Ocean, however, Drake Passage is a wide region that is not blocked by land, so no large-scale, east–west, sea surface tilt can develop. However, the wide continental shelves of Drake Passage and the submarine ridges east of the Passage close off essentially all of the pathways beneath 1 km along each latitude. Therefore, only the near-surface flow is unblocked and deep pressure gradients may develop.

In spite of this early explanation, dynamicists disagree about the details. One issue is the mechanism by which the momentum added by the wind near the surface is transferred to the deep ACC where it can be removed by the ocean bottom. Transient mesoscale eddies (about 150 km in diameter) and fixed pressure distributions (standing eddies) each transfer momentum towards the bottom. A second issue involves the importance of structure of the wind (the wind stress curl) which differentially transfers near-surface water equatorward and produces part of the vertical overturning in the Southern Ocean. It is argued that, similar to other ocean basins, the wind curl drives the ocean (called the Sverdrup Balance) and leads to good estimates of ACC location and total transport. Bottom topography in this view allows deep circulation across the ACC. However, another argument is that this view misses the momentum balance and ignores the effect of water pressure pushing on the solid earth thereby retarding the ocean flow.

In either view, the circulation in the Southern Ocean responds strongly to variations in bottom depth, unlike lower latitude oceanic regions. The near surface flow (**Figure 3**) is along submarine ridges and tends to cross ridges at gaps (for example, in the south-western Pacific between 140°W and 160°E). Because of the rotation of the earth, a column of water that stretches will spin faster in the direction of the Earth's spin (counterclockwise looking down on the ocean in the southern hemisphere). To avoid these changes, ocean flow tends to be along lines of constant depth (specifically, along lines of constant planetary vorticity (PIV) defined as the Coriolis parameter divided by depth).

Role In Global Thermohaline Circulation

The circulation of the global ocean is driven by two basic mechanisms: surface wind stress and dense water creation. Surface cooling and ice formation at high latitudes (in the Greenland, Norwegian, and Labrador seas and in the Weddell and Ross Seas) creates dense water which sinks into the deep ocean. These waters move along a variety of paths, mix with surrounding water, become less dense, and eventually return to the surface. The ACC participates in this circulation by mixing water among the major ocean basins and by providing a path for dense water (North Atlantic Deep Water) to return to the surface (along the tilting density surfaces seen in **Figure 2C**, as shown schematically in **Figure 4**).

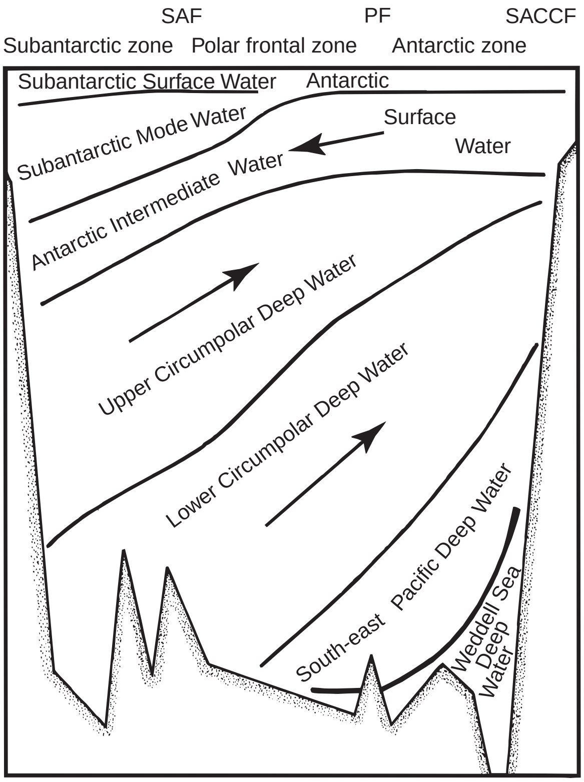

Figure 4 Water masses and bounding density surfaces in the Antarctic Circumpolar Current (ACC) at Drake Passage. Arrows indicate the direction of secondary flow along density surfaces across the ACC. Approximate locations of fronts are indicated. (Modified after Sievers and Nowlin, 1984.) SAF, Subantarctic Front; PF, Polar Front; SACCF, Southern ACC Front.

Less extreme surface cooling over and north of the ACC creates water that is driven northward by the surface winds and pushed below the surface to intermediate depths (1 km or so) driving additional circulation. Cold water near the surface in the southern ACC is driven north by the wind and eventually sinks under the warmer water to the north creating Antarctic Intermediate Water (**Figure 4**).

This secondary, north–south circulation is weak compared to the stronger eastward flow of the ACC, but is clearly indicated in the diagram (**Figure 4**) showing water masses and bounding density surfaces in a vertical section across Drake Passage. It plays an important role in the southward transport of heat and salt needed to balance the heat lost to the atmosphere and the freshening due to precipitation and ice melting. It also distributes throughout the interior ocean carbon dioxide and other trace gases entering the ocean at the surface. Deep water that rises near the surface provides a source of nutrients that are used by phytoplankton which form the basis of the Southern Ocean ecosystem.

Circumpolar Fronts

Ocean fronts are locations at which water properties change over short distances (a few tens of km), and are usually associated with boundaries between ifferent types of water. The ACC is known to have three distinct fronts that are continuous around the Southern Ocean. These fronts are labeled, from north to south, Subantarctic, Polar and Southern ACC fronts (**Figures 1** and **2**). The water density increases southward across each front, creating a pressure gradient that is balanced by the Coriolis force from the strong eastward flow. Stronger gradients in the fronts give rise to stronger currents, so the fronts are associated with jets (high speed, narrow currents). Each of these fronts is observed in every section across the ACC independent of longitude. In some places, however, they are so close together that they form a single front. Downstream, the fronts again separate with no indicated change in characteristics.

The Subantarctic Front (SAF) occurs where cold fresh water near the surface is denser than water to the north and thus descends into the interior, creating Antarctic Intermediate Water indicated by a distinct minimum in salinity at 400 m just north of the front (**Figure 2B**). Additional indicators are a northward temperature increase (warmer than 4°C) at 400 m and a southward increase in near-surface dissolved oxygen (to greater than $7\,\mathrm{ml\,l^{-1}}$). The Polar Front (PF) is located where cold near-surface water (Antarctic Surface Water) moves northward and sinks beneath less-dense surface waters. The minimum temperature above 200 m is colder than 2°C south of the PF (**Figure 2A**). The depth of the temperature minimum increases from 125 m or less to greater than 200 m in crossing the front from south to north. The warm Circumpolar Deep Water is absorbed into the surface mixed layer at the Southern ACC Front (SACCF). North of the SACCF, the temperature maximum below 500 m is warmer than 1.8°C, whereas the deeper salinity maximum is above 34.73 (**Figure 2A** and **B**). A distinct dissolved oxygen minimum is observed below 500 m and the value at the minimum is below $4.2\,\mathrm{ml\,l^{-1}}$ north of the SACCF.

The processes responsible for the ACC fronts may be considered from two points of view. The water mass point of view focuses on the secondary (north–south) circulation of the ACC driven northward near the surface by winds and southward at depth by density differences. The dynamic point of view recognizes that the ACC is unstable to disturbances in which mesoscale eddies are ejected from the frontal jets by baroclinic instability. The result is that momentum is transferred to the frontal jets, increasing their speed and increasing the tilt of the density surfaces. Bottom topography influences this process either by creating the disturbances that grow into eddies or by changing the way in which the eddies interact. These points of view are not inconsistent because the acceleration of the ACC jets by eddies tilts the background density, thus increasing its horizontal gradient. The location at which the water is subducted is controlled by the density of the surface water and the location of the matching interior density surface. The eddy effect collects more density surfaces in a given place making it the likely location of subduction.

Circulation Variability

Estimates of the total transport of the ACC based on density measurements across Drake Passage, with the choice of zero flow at the bottom, are relatively constant at about 90 Sv (1 Sv is 1 million $\mathrm{m^3\,s^{-1}}$). This method only estimates the transport associated with those currents that change with depth. An unknown, and potentially large, depth-independent flow must also be estimated to obtain the total transport.

The total transport of the ACC was first estimated at Drake Passage in the late 1970s and early 1980s using measurements of density, current, and bottom pressure over time. The bottom pressure difference across the passage was related to total transport thereby extending the transport time series from 1977 to 1982 (with 1980 missing). The average transport over the cross-sectional area westward during this four-year record is 123 ± 10 Sv, only slightly different from the estimated value over the best 14 months with direct current estimates (**Figure 5**). To this should be added the estimate of 11 Sv transport through the nonmeasured part of the Drake Passage section, giving a total of 134 Sv. Most transport variation is due to changes in the slope of the free surface while the internal density structure remains relatively constant and supports 70% of the total transport. Observed changes in net sea surface slope across the passage result in 20–40 Sv changes of the ACC transport over periods of weeks to months.

A semiannual cycle in the transport is driven by a semiannual change in the wind stress, with two main transport peaks per year (mostly spring and fall) but with lesser peaks in many months (**Figure 5**). Lunar monthly and fortnightly tides in Drake Passage create small variations in transport and have a weak influence on the surface tilt.

The applicability of the Drake Passage transport studies to other parts of the ACC has not been demonstrated. The presumption has been that the ACC changes speed globally as the average strength of the Southern Ocean winds changes. Variations of sea surface height, measured from satellites, are less related with increasing distance between measurements or increasing time difference. Furthermore, global changes in the ACC were not found, making it unlikely that global wind variations drive longitudinally coherent changes in the ACC flow.

An analysis of dynamics in a longitudinally unbounded ocean, combined with results from two different realistic ocean models representing the Southern Ocean provide an explanation for the character of variability of the ACC. Transport variations with periods of 1–8 months occur by changes in the flow that is independent of depth. However, these changes follow lines of constant planetary vorticity (PlV), creating a global free circulation path. More correctly, flow follows PlV lines except in a few places, like Drake Passage, where the flow jumps from one PlV line to a nearby line of the same PlV value. Wind stress variations parallel to PlV lines drive transport variations in the ACC.

Wind stress was strongly correlated with transport changes in two realistic ocean models and with measurements of bottom pressure. Wind stress along PlV lines was most strongly correlated with model changes, but various area and longitudinal averages of wind stress or curl of the wind stress (tendency of the wind to spin the ocean) were also significantly correlated with transport changes. However, pressure variations due to density changes may mask any relationship between wind and pressure, making it difficult to measure the total transport of the ACC with bottom pressure measurements. Furthermore, fluctuations of the ACC transport were not coherent around the ACC for periods shorter than semiannnual.

ACC variability also occurs through the creation of mesoscale eddies (*see* **Mesoscale Eddies**), in which a strong current wraps around itself due to unstable lateral meandering of ocean jets. The average kinetic energy due to eddies is higher downstream (east) of large topographic features that block the flow (Drake Passage, Kerguelen Plateau). Locations of the PF for a period of 7 years were analyzed, revealing an average frontal width of around 45 km and a displacement from the average position of 120–150 km. In some places, the bottom topography limits the variability, basically requiring the ACC to flow through certain narrow gaps. Thus, eddies are an integral part of the dynamics of the ACC in providing a mechanism to narrow and accelerate frontal jets and acting as a mixing

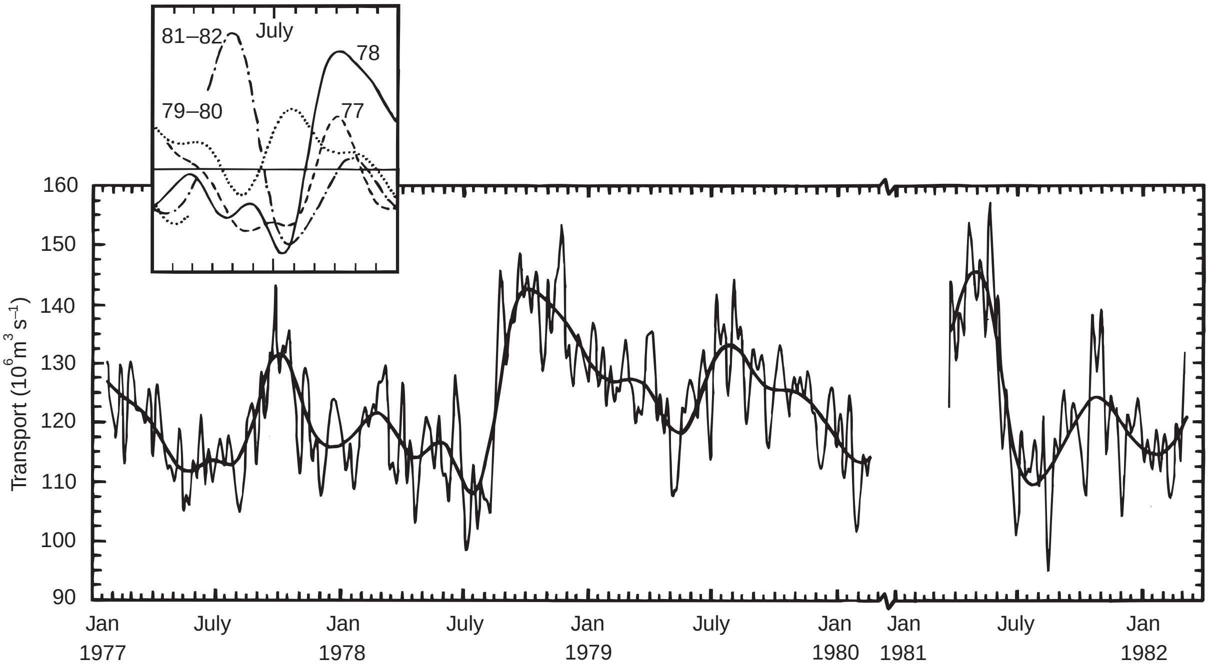

Figure 5 A time series (1977–1982) of volume transport through Drake Passage estimated from direct measurements of current, density, and bottom pressure. The insert allows easy comparison of transport variation in different years. (After Whitworth and Peterson, 1985.)

mechanism to redistribute water properties, including momentum.

At the end of the twentieth century, a number of laboratories in various countries were creating realistic numerical models of global ocean circulation for the purpose of testing ideas of ocean dynamics and to answer questions about the role of the ocean in the global climate. These models of necessity contain the Southern Ocean and are largely successful in creating an ACC-like flow in the observed location. However, all of these simulations overestimate the ACC transport by about 50%. Those models which allow mesoscale eddies to occur (although the dynamics of these small features are only marginally represented) have higher eddy energy in the proper places, compared to satellite measurements, but at magnitudes that are low by a factor of two or more.

Conclusions

The ACC is a large, variable flow around the Southern Ocean connecting the three major ocean basins. This current exchanges properties in the global ocean at the same time that it isolates Antarctica. It, thus, plays an integral role in the vertical overturning of the global ocean.

The large-scale structure of the ACC is clear in current observations and the details of the dynamical balance are largely understood, with a few disputes lingering. The time variability of the ACC is not well observed nor is the spatial structure of large-scale change known. Observation programs and numerical model studies are addressing these issues of variability.

See also

Mesoscale Eddies. Thermohaline Circulation. Weddell Sea Circulation. Wind and Buoyancy-forced Upper Ocean. Wind Driven Circulation.

Further Reading

Baker DJ Jr (1982) A note on Sverdrup balance in the Southern Ocean. *Journal of Marine Research* 40(suppl): 21–26.

Deacon G (1984) *The Antartic Circumpolar Ocean*. Cambridge: Cambridge University Press.

Fogg GE (1992) *A History of Antarctic Science*. Cambridge: Cambridge University Press.

FRAM Group (1991) An eddy-resolving model of the Southern Ocean. EOS, *Transactions of the American Geophysical Unions* 72(17): 169–175.

Gill AE and Bryan K (1971) Effects of geometry on the circulation of a three-dimensional southern hemisphere ocean model. *Deep-Sea Research* 18: 685–721.

Gille ST (1994) Mean sea surface height of the Antarctic Circumpolar Current from GEOSAT data; method and application. *Journal of Geophysical Research* 99(C9): 18 225–18 273.

Gille ST and Kelly KA (1996) Scales of spatial and temporal variability in the Southern Ocean. *Journal of Geophysical Research* 101(C4): 8759–8773.

Gordon AL, Molinelli E and Baker T (1978) Large-scale relative dynamic topography of the Southern Ocean. *Journal of Geophysical Research* 83(C6): 3023–3032.

Hofmann EE (1985) The large-scale horizontal structure of the Antarctic Circumpolar Current from FGGE drifters. *Journal of Geophysical Research* 90(C4): 7087–7097.

Hughes CW, Meredith MP and Heywood KJ (1999) Wind-driven transport fluctuations through Drake Passage: a southern mode. *Journal of Physical Oceanography* 29(8 part 2): 1971–1992.

Mikolajewicz U, Maier-Reimer E, Crowley TJ and Kim K-Y (1993) Effect of Drake and Panamanian gateways on the circulation of an ocean model. *Paleoceanography* 8(4): 409–426.

Moore JK, Abbott MR and Richman JG (1999) Location and dynamics of the Antarctic Polar Front from satellite sea surface temperature data. *Journal of Geophysical Research* 104(C2): 3059–3073.

Munk WH and Palmen E (1951) Note on the dynamics of the Antarctic Circumpolar Current. *Tellus* 3: 53–55.

Nowlin Jr, WD and Klinck JM (1986) The physics of the Antarctic Circumpolar Current. *Review of Geophysics and Space Physics* 24: 469–491.

Olbers D (1998) Comments on 'On the obscurantist physics of 'form drag' in theorizing about the Circumpolar Current'. *Journal of Physical Oceanography* 28(8): 1647–1654.

Orsi AH, Whitworth T III and Nowlin WD Jr (1995) On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Research I* 42(5): 641–673.

Peterson RG (1988) On the transport of the Antarctic Circumpolar Current through Drake Passage and its relation to wind. *Journal of Geophysical Research* 93(C11): 13 993–14 004.

Semtner AJ Jr and Chervin RM (1992) Ocean general circulation from a global eddy-resolving model. *Journal of Geophysical Research* 97: 5493–5550.

Sievers HA and Nowlin WD Jr (1984) The stratification and water masses at Drake Passage. *Journal of Geophysical Research* 89: 10 489–10 495.

Sinha B and Richards KJ (1999) Jet structure and scaling in southern ocean models. *Journal of Physical Oceanography* 29(6) 1143–1155.

Tomczak M and Godfrey JS (1994) *Regional Oceanography: An Introduction*. Pergamon Press.

Treguier AM and Panetta RL (1994) Multiple zonal jets in a quasigeostrophic model of the Antarctic Circumpolar Current. *Journal of Physical Oceanography* 24(11): 2263–2277.

van Loon H (1972) Half-yearly oscillations in the Drake Passage. *Deep-Sea Research* 19: 525–527.

Warren BA, LaCasce JH and Robbins PE (1996) On the obscurantist physics of 'form drag' in theorizing about the circumpolar current. *Journal of Physical Oceanography* 26(10): 2297–2301.

Whitworth T III (1983) Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage. *Journal of Physical Oceanography* 13: 2045–2057.

Whitworth T III and Peterson RG (1985) Volume transport of the Antarctic Circumpolar Current from bottom pressure measurements. *Journal of Physical Oceanography* 15(6): 810–816.

Whitworth T III and Nowlin WD Jr (1987) Water masses and currents of the Southern Ocean at the Greenwich Meridian. *Journal of Geophysical Research* 92(C6): 6462–6476.

ANTARCTIC FISHES

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doi:10.1006/rwos.2001.0016

Introduction

Antarctica is a continental land mass much of which is covered by an ice cap, consequently the ichthyofauna is totally marine. Surrounding the continent is the Southern Ocean, approximately 36 M km^2, continuous with the Atlantic, Indian, and Pacific Ocean basins to the north and whose northern limit is generally taken as the Antarctic Polar Frontal Zone (APFZ). There is a clear separation between the Antarctic and the Southern Hemisphere continents; the nearest connection being with South America via the Scotia Arc, a series of islands, separated from each other by deep water.

The Antarctic Circumpolar Current (ACC) and the general oceanographic regime mean that marine isotherms are more or less concentric around the continent. Close to the continent the seasonal variation in temperature is rarely more than 1°C whilst even at the northern limit, as for example at South Georgia, the range is little more than 4°C.

These two factors, geographical isolation and constant low temperature, have a major effect on Antarctic fish.

Fish Fauna

The Southern Ocean ichthyofauna is relatively sparse and unusual in composition, consisting of 213 species belonging to only 18 families (**Table 1**, **Figure 1**). Nearly half the species belong to one group, the perciform notothenioids, which make up 45% of the fish fauna. Restricting consideration to the shelf, and particularly in the highest latitudes, nototheniods make up 77% of the species and 90–95% of the biomass of fish. Notothenioids are morphologically and ecologically diverse and have diversified into a wide variety of niches, mainly demersal, but also in the water column and even within sea ice. As a group this makes them more diverse than, for example, the finches of the Galapagos Archipelago. The concept of species flocks has been developed for freshwater fish to identify groups that have a close affinity; typically such flocks are to be found in ancient lake systems and it is extremely unusual for such a flock to be identified from a large marine environment. Antarctic notothenioids with their high species diversity

Table 1 Composition of Southern Ocean ichthyofauna

Taxon	*Benthic*	*Benthopelagic*	*Pelagic*
Agnatha	2		
Chondrichthyes	8	2	1
Osteichthyes			
Notacanthiformes		2	
Anguilliformes		2	
Salmoniformes	4		5
Stomiiformes			12
Aulopiformes			9
Myctophiforms			35
Gadiformes	9	11	1
Ophidiiformes	1		1
Lophiiformes			3
Lampriformes			2
Beryciformes			6
Zeiformes		1	
Scorpaeniformes	32		
Perciformes			
Zoarcidei	22		
Notothenioidei	95		
Blennioidei	1		
Scombroidei			2
Stromateoidei			1
Pleuronectiformes	4		