Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 1349-1354.

THE GLOBAL INFLUENCE OF THE SOUTHERN OCEAN CIRCULATION

S. R. Rintoul*
CSIRO Marine and Atmospheric Research and Antarctic Climate and Ecosystems CRC, Hobart, Australia

1. INTRODUCTION

The accident of geography that creates a circumpolar channel of ocean at the latitude of Drake Passage has a profound impact on global ocean circulation patterns and climate. The strong eastward flow of the Antarctic Circumpolar Current (ACC) connects the ocean basins, allowing the existence of a global-scale overturning circulation that carries most of the ocean heat transport. The tilting of density surfaces associated with the geostrophic flow of the ACC brings dense water to the surface at high latitudes. Water mass transformations where these layers outcrop link the upper and lower limbs of the overturning circulation. Water masses exported from the Southern Ocean ventilate the deep and intermediate layers of the ocean and play an important part in global budgets of heat, freshwater, carbon and nutrients. Recent progress in understanding the circulation of the Southern Ocean and its role in climate variability and change is reviewed.

2. MAIN FEATURES OF THE SOUTHERN OCEAN CIRCULATION

Figure 1 shows a schematic view of the global ocean circulation, from a Southern Ocean perspective. The ACC circles Antarctica from west to east, providing the primary pathway for exchange of water masses between the ocean basins. The interbasin exchange provided by the ACC transforms the large-scale ocean circulation and heat transport from a regional to a global phenomenon.

Figure 1 also shows the zonally-averaged circulation in different layers in each of the ocean basins, which together make up the global overturning or thermohaline circulation. Deep water formed in the North Atlantic (NADW) is carried south to the Southern Ocean. The NADW is carried eastward by the ACC and also spreads poleward along shoaling isopycnals to outcrop at the sea surface near Antarctica. At the isopycnal outcrop, exchange of heat and moisture between the ocean and the overlying atmosphere and sea ice converts the upwelled deep water to dense Antarctic Bottom Water (near Antarctica) or to lighter intermediate waters (at lower latitudes). The new Southern Ocean water masses carry oxygen-rich waters into the interior to ventilate approximately 50% of the global ocean volume. The intermediate waters carried north in the Atlantic basin balance the outflow of NADW and so close the overturning circulation in the Atlantic.

The ACC and the Southern Ocean overturning circulation influence global climate in several key ways: the ACC connects the ocean basins, allowing a global-scale overturning circulation to exist and providing an oceanic teleconnection for the transmission of climate signals; the conversion of deep water to intermediate water by air-sea exchange in the Southern Ocean completes the overturning circulation associated with NADW production and export; and Southern Ocean water masses regulate the ocean uptake of oxygen, carbon dioxide and heat.

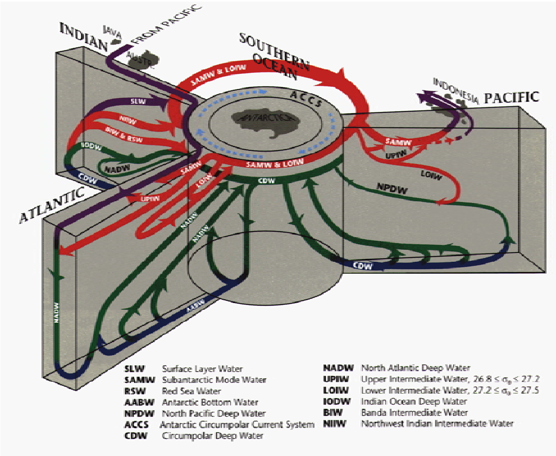

Figure 1: A schematic view of the global overturning circulation, from Schmitz (1996). The ACC is indicated by the wide, red arrow circling Antarctica. The zonally-averaged circulation in each basin is indicated by the arrows, with a different color used for each water mass (roughly, waters of similar density). The circulation in the deep ocean is connected to the upper ocean primarily by water mass transformation in the Southern Ocean, with a more modest contribution from mixing at low latitudes.

3. THE ANTARCTIC CIRCUMPOLAR CURRENT: THE OCEAN'S ANNULAR MODE

A common feature of planetary atmospheres is the existence of zonal jets or annular circulations. The presence of continents prevents the establishment of such circulations in the ocean, except in the latitude band of Drake Passage. Here the ACC provides an oceanic analog for the annular modes in the Earth's atmosphere.

* *Corresponding author address:* Stephen R. Rintoul, CMAR and ACE CRC, GPO Box 1538, Hobart, Tasmania, 7001, Australia; e-mail:steve.rintoul@csiro.au

A simplified view of the main Southern Ocean currents is shown in Figure 2. The ACC is a deep-reaching current made up of several jets or fronts. The ACC carries more water than any other ocean current: 147±10 Sv south of Australia (Rintoul and Sokolov, 2001) and 137±9 Sv south of Africa and South America (Cunningham et al., 2003) (1 Sv = 10^6 m^3 s^{-1}; 1 ACC = 85,714 times the annual mean flow over Foz do Iguaçu). The difference of 10 Sv balances the Indonesian Throughflow, the only pathway for interbasin exchange of warm water.

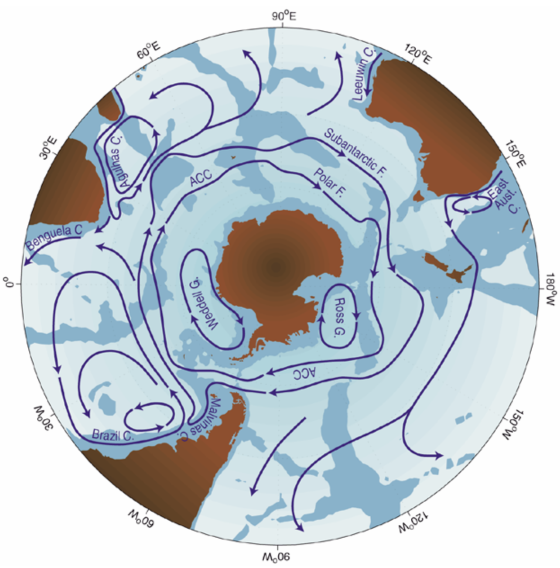

Figure 2: A schematic view of the main Southern Ocean currents. The ACC coincides with the Subantarctic and Polar fronts in this simplified representation. The ACC interacts with the cyclonic subpolar gyres to the south of the current and the anticyclonic subtropical gyres to the north. From Rintoul et al., 2001.

The traditional picture of the ACC derived from hydrographic sections is of two circumpolar current cores, coincident with enhanced gradients in water properties (ie fronts), as illustrated in Figure 2. This image of two continuous circumpolar fronts has been hard to reconcile with high resolution ocean circulation models, which have tended to reveal a more complex, multi-filamented current structure. Recent analysis of high resolution satellite observations of sea surface temperature (Hughes and Ash, 2001) and sea surface height (Sokolov and Rintoul, 2002; 2006) suggest the mean ACC is in fact made up of multiple filaments, reminiscent of high resolution simulations (Figure 3).

Although complex, the frontal structure of the ACC is also robust: maxima in the gradient of sea surface height (and therefore in current speed) tend to be found along particular streamlines and the jets coincide consistently with water mass features traditionally used to define the fronts. The two main fronts of the ACC, the Subantarctic and Polar Fronts, are made up of two or three branches, which merge and diverge along the circumpolar path of the current. The recognition that the ACC consists of multiple, persistent zonal flows which coincide with particular water mass structures helps to reconcile the hydrographic and dynamical views of the current. The zonation of the ACC is an expression of the tendency for baroclinically active quasi-geostrophic turbulence to organize into zonal jets (eg Rhines, 1975). In the case of the ACC, the structure of the flow also depends on topographically controlled stationary eddies (eg Treguier and Panetta, 1994).

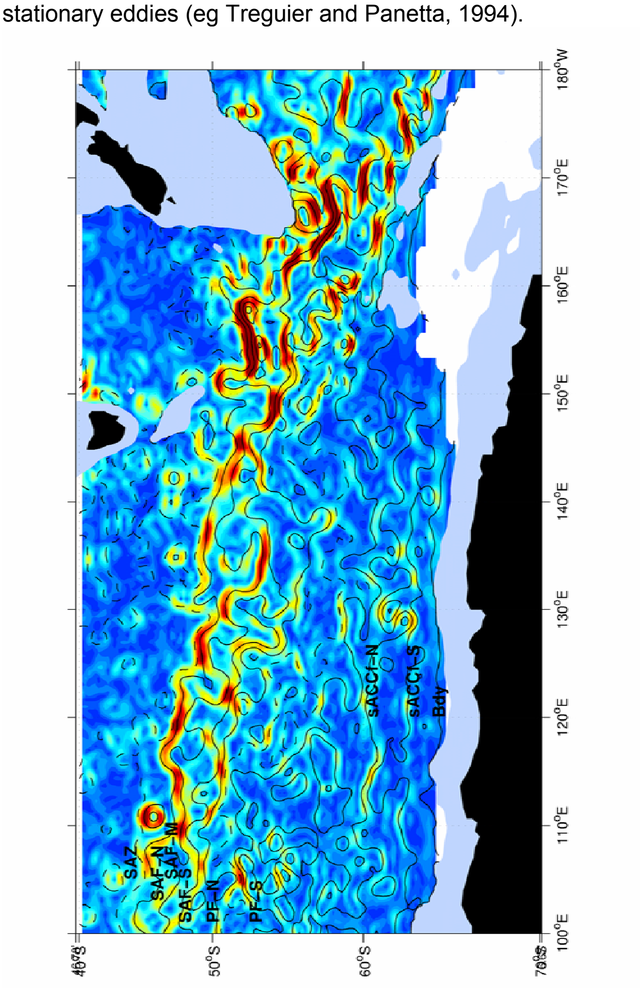

Figure 3: A synoptic map of the gradient of sea surface height (color), showing the multiple jets of the ACC between 100°E and 180°E. The distribution of gradient maxima in a 12-year sequence of such maps is strongly peaked at particular values of sea surface height (black contours), which coincide with branches of the primary ACC fronts. SAF = Subantarctic Front; PF = Polar Front; sACCf = southern ACC Front; N = north; M = middle; S = south. (Sokolov and Rintoul, 2006).

While the similarity between the ACC and zonal jets in the atmosphere was noted decades ago (eg Williams, 1978), the extent of the dynamical analogy is now more fully appreciated. As in the atmospheric case, eddies play a key role in the dynamics of the ACC (Rintoul et al., 2001). The lack of continents in the latitude band of Drake Passage means there can be no zonal pressure gradients and hence no north-south mean flow above the depth of the bathymetry. Eddies therefore provide most of the poleward heat flux. The eddies also carry momentum downward, driving deep flows. The pressure gradients associated with these deep geostrophic flows produce a form stress acting on the bathymetry, which acts to balance the wind stress acting at the sea surface. Finally, the eddies carry mass poleward across the ACC as part of the "residual mean" meridional circulation that is driven by the net buoyancy forcing at the surface of the ocean (eg Karsten et al., 2002; Olbers et al. 2004; Rintoul et al., 2001) The zonal flow of the ACC and the overturning circulation in the meridional plane are therefore intimately linked and the dynamics cannot be understood if either aspect of the Southern Ocean circulation is considered in isolation.

4. THE SOUTHERN OCEAN OVERTURNING CIRCULATION

The two counter-rotating cells of the Southern Ocean overturning circulation are illustrated in Figure 4. Deep water upwells on the southern flank of the ACC and is driven north in the Ekman layer, where it gains heat and precipitation from the atmosphere and becomes less dense. The lighter surface waters ultimately subduct and are exported to lower latitudes at intermediate depth, forming the upper cell of the Southern Ocean overturning circulation. Denser varieties of deep water upwell further south, close to Antarctica, where heat loss and brine released during sea ice formation make the surface waters more dense. The production of dense Antarctic Bottom Water near Antarctica forms the sinking branch of the lower cell of the Southern Ocean overturning.

For the last 50 years, our conceptual models of the deep ocean circulation have assumed that the sinking of deep water in the North Atlantic was compensated by weak upwelling distributed uniformly over the low latitude thermocline (eg Stommel and Arons, 1960). Direct observations have now shown that diapycnal mixing in most of the ocean is an order of magnitude too weak to compensate the sinking at high latitude (eg Ledwell et al., 1993). The Southern Ocean provides a solution to this conundrum: deep water rises to the surface in the Southern Ocean and is converted to lighter water by buoyancy supplied by the atmosphere, rather than by mixing in the ocean interior. Recent diagnostic studies based on ocean observations and a variety of numerical simulations agree that water mass transformation in the Southern Ocean links the deep and shallow branches of the global overturning circulation, although the strength of the Southern Ocean overturning remains a topic of debate.

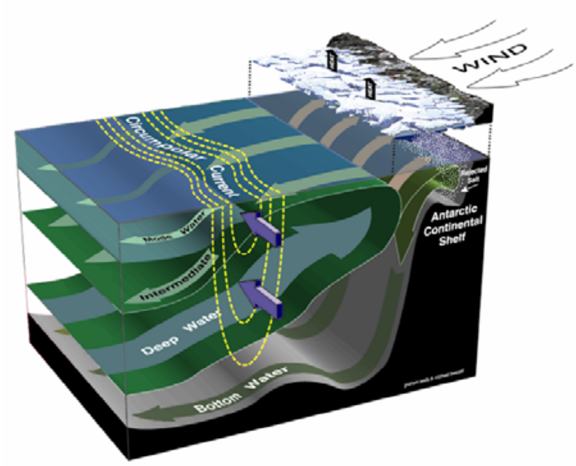

Figure 4: A schematic north-south slice across the Southern Ocean, illustrating the two counter-rotating cells of the overturning circulation. The conversion of deep water to intermediate water and bottom water is driven by exchange of heat and moisture (precipitation, evaporation and sea ice formation and melt) at the sea surface.

Figure 5 shows a representation of the key processes involved in the Southern Ocean overturning, as inferred from a relatively coarse resolution ocean model (Iudicone et al., 2006). The details of the overturning get quite complicated. In addition to buoyancy exchange at the sea surface, mixing plays an important role in the water mass transformations involved in the overturning. Eddy fluxes (parameterized in this model) are also important. But the overall pattern is consistent with the schematic shown in Figure 4: upwelling of deep water balanced by sinking and export of lighter intermediate water and denser bottom water, forming two counter-rotating cells. In this model, 80% of NADW ultimately upwells and is converted to lighter water in the Southern Ocean (half takes a direct route from the Atlantic to the Southern Ocean and half takes a more circuitous route through the Indian and Pacific basins prior to upwelling in the Southern Ocean). The remaining 20% upwells through the thermocline at lower latitude.

The idea that the ocean gains buoyancy at high southern latitudes, as required to drive the upper overturning cell, has been met with some skepticism. The air-sea fluxes are indeed poorly known due to the lack of observations. Nevertheless, most climatologies derived from observations or from reanalyses of atmospheric forecast models agree that part of the Southern Ocean gains heat from the atmosphere. This makes oceanographic sense, provided the equatorward Ekman transport is not completely compensated by eddy fluxes: cold water upwells in the south and is driven north in the Ekman layer beneath a warmer atmosphere, thereby gaining heat. At higher latitude, near the Antarctic continent, the ocean loses heat. All present climatologies agree that there is a net excess of precipitation over evaporation over the Southern Ocean. The net result of freshwater input and warming (or at least weak cooling) is that the ocean gains buoyancy (eg Large and Nurser, 2001).

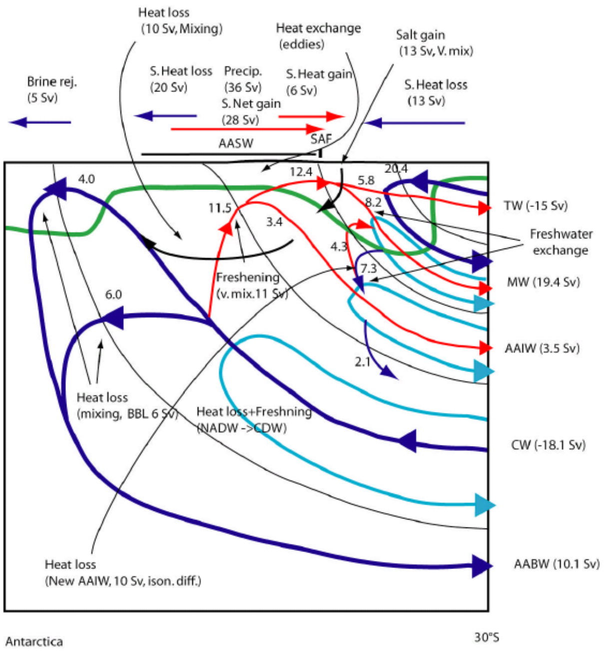

Figure 5: A schematic view of the Southern Ocean overturning circulation in a coarse resolution ocean model, showing the key processes involved in water mass transformation. The base of the mixed layer is shown by the green line. The black lines delineate density layers corresponding to major water masses (TW = thermocline water; MW = mode water; AAIW = Antarctic Intermediate Water; CW = circumpolar deep water; AABW = Antarctic Bottom Water). From Iudicone et al., 2006.

The asymmetry between the air-sea heat flux at equivalent latitudes in the two hemispheres can be explained by the continental geometry: in the northern hemisphere, winter outbreaks of cold, dry continental air result in strong cooling, particularly over the warm waters carried poleward by ocean currents; in the maritime southern hemisphere, fluxes are more modest and of the opposite sign because of the lack of continental outbreaks and the fact that poleward movement of warm water is blocked by the Drake Passage gap and the ACC.

The global overturning circulation plays a dominant role in the climate system because it transports large amounts of heat. The Southern Ocean contribution is to link the upper and lower limbs of the global cell. However, the overturning carries more than heat. Water exposed to the atmosphere absorbs oxygen, carbon dioxide and other tracers and carries these properties into the ocean interior when the water sinks. The sinking branch of the upper cell (ie the formation and export of mode and intermediate water) helps to sequester heat and carbon dioxide on the northern flank of the ACC (Levitus et al., 2005; Sabine et al., 2004): about 40% of the total ocean storage of anthropogenic carbon dioxide is found south of 30S. The upwelling of nutrient-rich deep water and export in intermediate water is also the main pathway by which nutrients are returned from the deep ocean to the surface layers, fueling 75% of ocean primary production north of 30°S (Sarmiento et al., 2004).

5. SOUTHERN OCEAN VARIABILITY AND CHANGE

Southern Ocean variability and change is likely to have impacts on regional and global climate, given the influence of the Southern Ocean on the global circulation patterns that regulate the budgets of heat, moisture and carbon. While the lack of observations makes the detection and attribution of Southern Ocean change a challenging task, there is growing evidence that changes are underway. Most of the Southern Ocean has warmed in recent decades (Gille, 2002; Levitus et al., 2004). The largest changes in heat content in the southern hemisphere oceans are found on the northern flank of the ACC, reflecting the transmission of the global warming signal into the ocean interior by the subduction of Southern Ocean water masses.

Parts of the Southern Ocean have become significantly fresher in recent decades (Wong et al., 1999; Curry et al.,2003). Shelf waters in the Ross Sea have steadily freshened since the late 1960s (Jacobs et al., 2002). The decrease in salinity has been attributed to enhanced basal melt of floating ice shelves in the southeast Pacific caused by warmer ocean temperatures (eg Shepherd et al., 2004). The freshening of shelf waters in bottom water formation regions in the Indian and Pacific Oceans has resulted in a rapid shift in the temperature – salinity properties of the deep ocean (Aoki et al., 2005).

Interest in the polar freshwater balance is high because of the possibility that freshening could slow down or halt the sinking branch of the global overturning, as has happened in past climates. The salinity of dense water sinking in the North Atlantic has steadily decreased over the last four decades (Dickson et al., 2002) and a recent study has reported a 30% decline in the rate of the Atlantic overturning circulation over this period (Bryden et al., 2005). The rate of freshening of dense water formed in the Indian sector of the Southern Ocean is comparable to that observed in the North Atlantic; however, the lack of any change in oxygen concentrations suggests there has so far been no reduction in the ventilation by Antarctic Bottom Water.

A number of recent studies of southern hemisphere climate variability have focused on the Southern Annular Mode (SAM) and its oceanographic consequences. The SAM is the dominant mode of variability in the high latitude southern hemisphere atmosphere. The SAM has trended toward its positive state over the last 30 years, corresponding to a poleward shift and strengthening of the surface westerlies. The trend to date appears most likely to be caused by the decline in stratospheric ozone over the same period (Thompson and Solomon, 2002), although enhanced greenhouse warming may also have played a role (eg Fyfe et al., 1999). The changes in wind forcing of the ocean by the SAM have been linked to changes in ocean circulation and sea ice (eg Hall and Visbeck, 2002). It is possible that many of the changes observed in the Southern Ocean are linked to changes in the SAM, including a poleward shift in the ACC (Gille, 2002) and increased upwelling of relatively warm water due to enhanced Ekman divergence south of the ACC. Changes in northern hemisphere climate in recent decades have also been linked to a trend in the northern hemisphere equivalent of the SAM. However, the cause of the trend remains a topic of active debate.

6. SUMMARY

The Southern Ocean links the upper and lower limbs of the global overturning circulation and therefore has a substantial influence on the mean climate and budgets of heat, moisture and carbon. The ACC is the closest dynamical analog in the ocean to the zonal flows in planetary atmospheres, a fact that oceanographers are only starting to exploit. For example, observations suggest that the ACC tends to form multiple zonal jets that merge and diverge along the circumpolar path of the current, reminiscent of the tendency towards zonation in simulations of quasi-geostrophic turbulence. The Southern Ocean is warming and freshening. Both the northern and southern ends of the global overturning circulation are responding to changes in the freshwater balance at high latitudes. Whether natural or anthropogenic factors are driving the changes in the Soutehrn Ocean remains a topic of active debate.

ACKNOWLEDGEMENTS

This study was supported by the Cooperative Research Centre program of the Australian government through the Antarctic Climate and Ecosystems CRC, by the CSIRO Climate Change Science Program funded in part by the Australian Greenhouse Office of the Department of Environment and Heritage, and by the CSIRO Wealth from Oceans National Research Flagship.

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