

POSITION ANALYSIS

Climate change and the Southern Ocean



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EXECUTIVE SUMMARY

The world's oceans have a remarkable capacity to absorb heat and carbon dioxide. More than 90% of the extra heat energy stored by the planet in the last 50 years, and about 30% of the carbon dioxide released by human activities over the same period has been absorbed in the ocean. By absorbing heat and carbon dioxide, the oceans have slowed the rate of climate change.

The Southern Ocean, which connects the Atlantic, Indian and Pacific Oceans, is defined variously in different studies. Here we consider it as that region south of 30°S (Bindoff et al., 2007). This latitudinal band stores more heat and carbon dioxide than any other latitude band on Earth. The dominant influence of the Southern Ocean on global climate and the carbon cycle is the result of the unique ocean currents in this region, which efficiently transfer heat and carbon from the surface to the deep ocean.

Given the critical role of the Southern Ocean in the Earth's climate system, changes in the Southern Ocean have global ramifications. In fact, changes are already under way. The Southern Ocean has warmed and freshened, become more acidic and ocean circulation patterns have changed. Changes in marine ecosystems in the Southern Ocean have been linked to these changes.

Many of the changes observed in the Southern Ocean in recent decades have been caused by changes in wind patterns, which in turn are linked to both the ozone hole and to the increase in greenhouse gases in the atmosphere. Climate models suggest that the Southern Ocean will continue to evolve in response to greenhouse warming, resulting in further ocean warming and freshening, higher sea level, less sea ice and changes in ocean currents.

However, many uncertainties remain with regard to the response of the Southern Ocean to climate change and the consequences of Southern Ocean change. One key scientific uncertainty is the likelihood and magnitude of feedbacks to the climate system as a result of Southern Ocean changes. Feedbacks may occur due to changes in ocean circulation, the rate of carbon uptake by the ocean, reduction in sea-ice extent and the potential for a warmer ocean to accelerate the loss of ice from the Antarctic ice sheet and therefore cause ocean freshening and sea-level rise. Warming and ocean acidification (the lowering of the ocean's pH as the rate of carbon uptake increases) will also impact on marine ecosystems.

Southern Ocean processes are intimately linked to some of the most pressing challenges faced by society: climate change, sea-level rise, ocean acidification and the sustainable management of marine resources. To address these challenges, we need to improve our understanding of the nature, causes and consequences of Southern Ocean change. New observing systems and sustained observations, which can only be maintained through international collaboration, plus advances in climate modelling that assimilate and integrate these observations, are improving our knowledge of Southern Ocean

processes and changes. Continued investment in long-term Southern Ocean observations and related modelling will have significant dividends for society in understanding our changing climate.

THE ROLE OF THE SOUTHERN OCEAN IN THE EARTH SYSTEM

The world's oceans moderate global climate through their capacity to absorb heat and carbon dioxide, thereby slowing the effects of carbon emissions from human activities. Since the 1960s, when most of human carbon emissions have been made, the oceans have stored 90% of the extra heat in the earth system (Bindoff et al., 2007) and nearly 30% of the total CO₂ emitted from fossil-fuel use, cement manufacturing and anthropogenic land use changes (Global Carbon Project, 2010). In 2009, the world's oceans were absorbing 26% of industrial CO₂ emissions (Global Carbon Project, 2010).

The oceans of the Southern Hemisphere are particularly important for storing and transporting vast amounts of heat and carbon. The Southern Ocean (south of 30°S) absorbs about 40% of the total global ocean uptake of anthropogenic CO₂ (Gruber et al., 2009). The widespread influence of the Southern Ocean is the result of the unique ocean currents in the region. The Antarctic Circumpolar Current (ACC), the largest current in the world ocean, flows from west to east around Antarctica and connects the basins of the Atlantic, Indian and Pacific Oceans (Figure 1). This connection has a profound effect on global ocean circulation patterns and climate.

The Southern Ocean also connects the shallow and deep parts of the ocean (Figure 2). Water spreads from north to south and rises towards the surface across the ACC. When it reaches the surface, the water takes one of two paths: moving southward where it becomes cold and salty enough to sink to the deep ocean, or moving northward where it becomes warmer and fresher, ultimately sinking on the northern side of the ACC and spreading north at intermediate depths in the ocean. This pattern of two counter-rotating cells is known as the overturning circulation (Figure 2).

The overturning circulation largely sets the capacity of the Southern Ocean to store heat and carbon. Where water sinks from the sea surface, heat, carbon and oxygen absorbed from the atmosphere are carried into the ocean. Where water upwells, these properties can be released to the atmosphere. The overall capacity of the ocean to store heat and carbon is set by the balance between the upwelling and downwelling circulation. The overturning circulation is a very efficient means of transporting heat: the volume of flow of warm water in the upper ocean is balanced by the volume of flow of cold water in the deep ocean, resulting in a net transport of heat from the equatorial regions towards the poles. This makes the equatorial regions cooler and the poles warmer than they would otherwise be, and the Earth as a whole more habitable. The transport of heat and moisture by the ocean and atmosphere in turn sets the large-scale patterns of temperature, rainfall and evaporation that determine regional climate.

The large-scale circulation in the Southern Ocean that controls the overturning circulation through Antarctic Bottom Water formation (lower limb), and the formation of the Mode and Intermediate waters (upper limb), play a key role in the distribution of heat and carbon in the global ocean and therefore in climate processes and change. The sinking of oxygen-rich surface waters in the Southern Ocean is also the primary way that oxygen levels in the deep ocean are maintained.

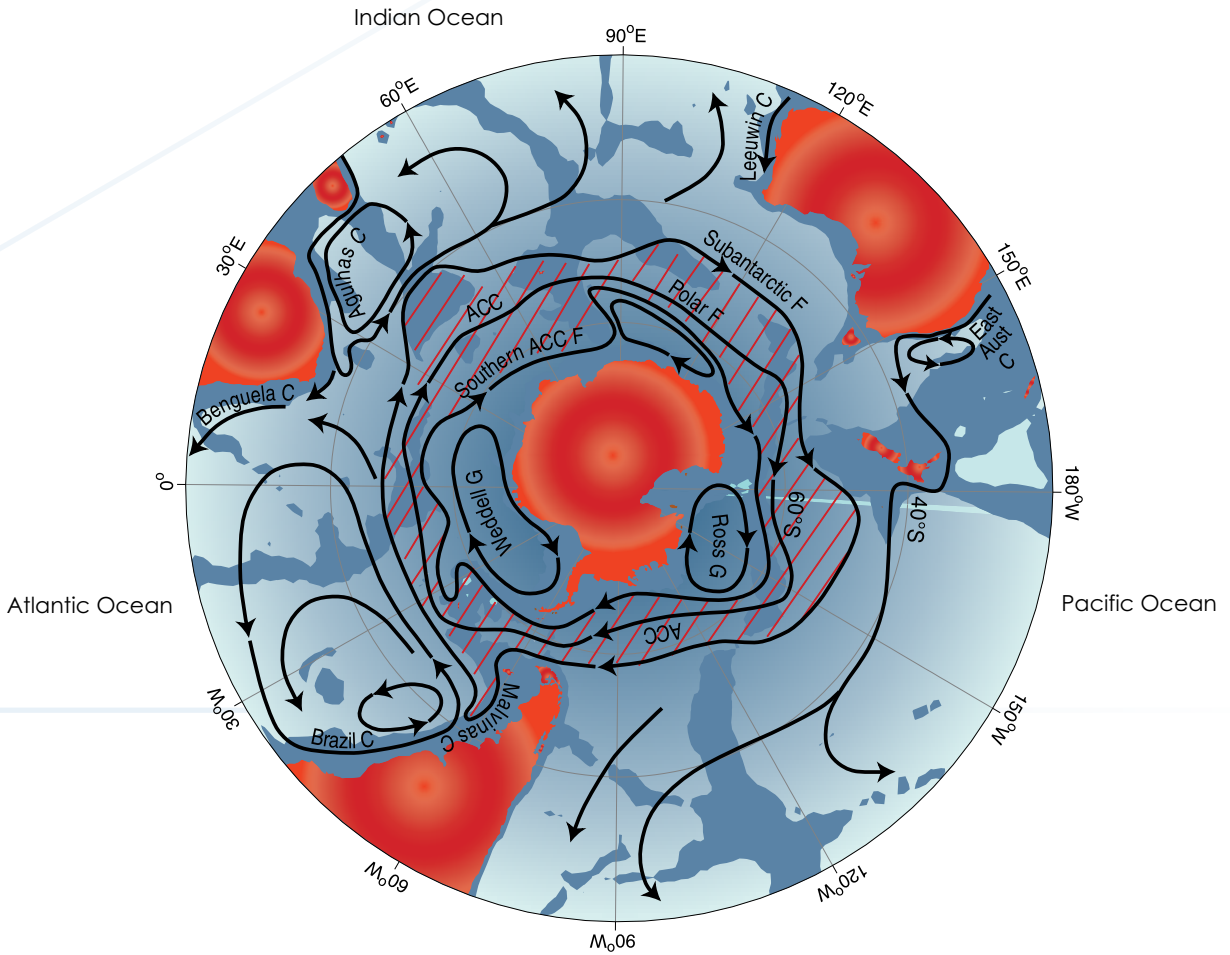


Figure 1. The Southern Ocean showing the mean surface flow features: the hatched area shows the broad-scale flow in the ACC . Dark (light) blue regions show ocean depths less (greater) than 2000 m. C = Current (e.g. ACC = Antarctic Circumpolar Current); F = Front; G = Gyre. (Rintoul, 2011)

THE UPPER AND LOWER LIMBS OF THE SOUTHERN OCEAN OVERTURNING CIRCULATION (REFER FIG 2).

The “lower limb” of the Southern Ocean overturning circulation is driven by cold, dense Antarctic Bottom Water, formed near the Antarctic coast. Antarctic Bottom Water is formed where cold off-shore winds drive the sea-ice northward, creating narrow, ice-free regions known as coastal ‘polynyas’. The ice is driven northward as soon as it grows. It does not form an insulating blanket on the ocean surface and therefore paradoxically polynyas have very high rates of sea-ice production. Salt ejected during sea-ice growth is added to the underlying water, making it saltier and therefore denser. During winter the density increases until the waters sink and flow down the continental slope onto the deep abyssal plains that surround the Antarctic continent. Antarctic Bottom Water is transported into surrounding major ocean basins (Figure 2), and eventually mixes with approximately 30% of the total volume of the global oceans.

The “upper limb” of the Southern Ocean overturning circulation is formed from surface waters that are driven northwards across the Antarctic Circumpolar Current (ACC) by the combination of westerly winds and the Earth’s rotation. The surface waters sink into the ocean interior on the northern side of the ACC. This process, known as subduction, is driven by a combination of wind forcing, eddy transport, and changes in the depth of the surface mixed layer along the direction of flow. The subducted waters from the Southern Ocean (which are called Mode Water and Intermediate Water, Figure 2) mix with about 10% of the global ocean volume. Together with Antarctic Bottom Water, this means that Southern Ocean and Antarctic waters affect 40% of the global ocean volume.

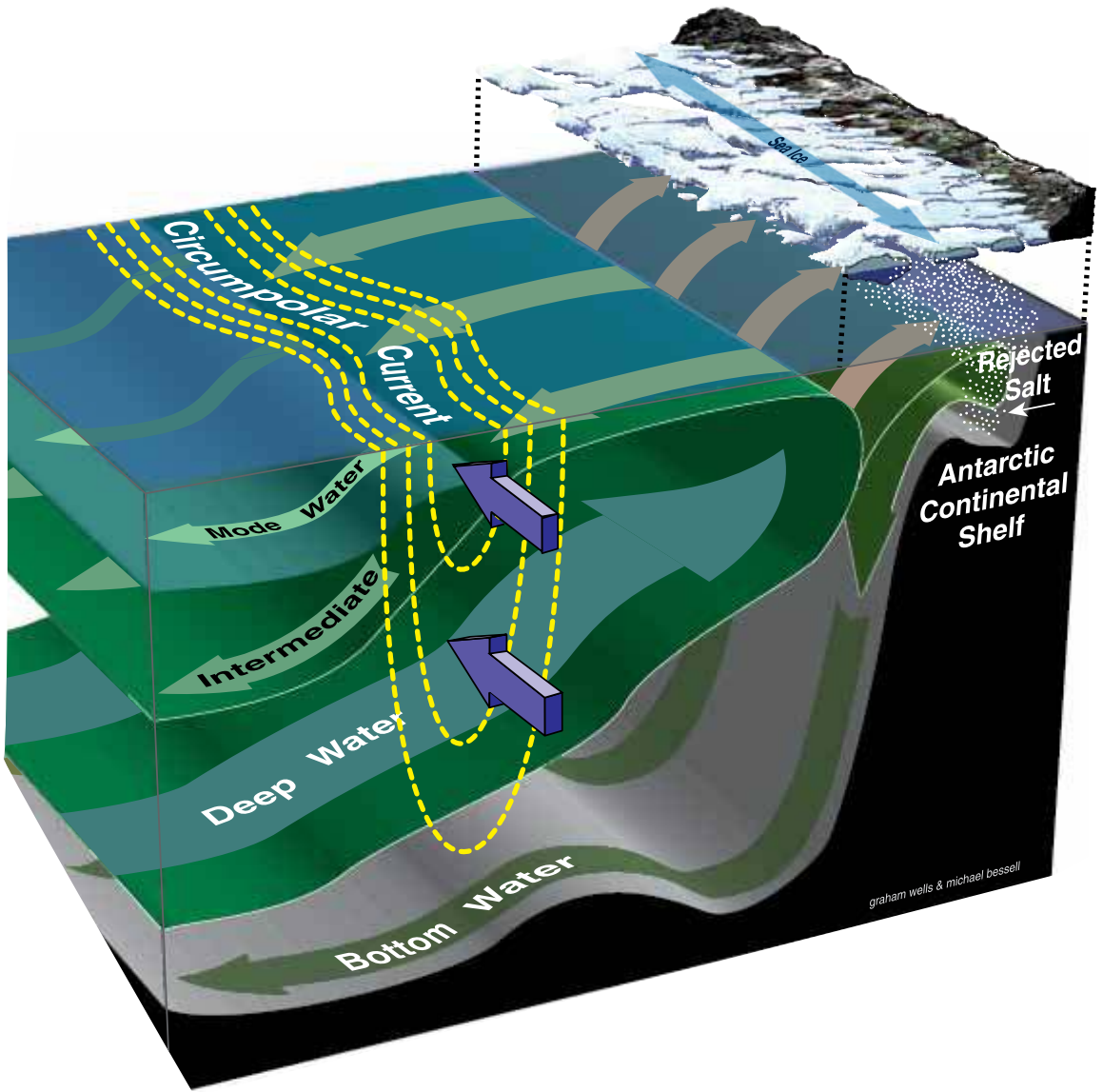


Figure 2. A cross-section of the Southern Ocean from north of the Antarctic Circumpolar Current to the Antarctic continent. Deep water rises to the surface across the Antarctic Circumpolar Current and then takes one of two paths. It may move southward, where salt rejected during sea-ice formation over the Antarctic Continental Shelf creates dense water that flows down the continental slope to form Antarctic Bottom waters. This is the lower limb of the Southern Ocean Overturning Circulation (shown on the right of the figure). Alternatively, it can move northward across the ACC before sinking and spreading at mid-depths as Mode or Intermediate waters (the upper limb, left of the figure).

RECENT CHANGES TO THE SOUTHERN OCEAN

Observations over the past 50 years show that the Southern Ocean is changing. These changes include:

- warming and freshening throughout most of the ocean depth (Gille, 2008; Böning et al., 2008; Meijers et al., 2011);
- a shift of major currents to the south (Sokolov and Rintoul, 2009a,b), which may have driven a change in the distribution of organisms (Cubillos et al., 2007) and carried more heat southward to melt ice around the rim of Antarctica (Jacobs, 2006);
- changes to the acidity of the ocean as extra CO₂ is absorbed in the water, and consequent impacts on marine organisms (ACE CRC, 2008; Bindoff et al., 2007); and
- potential future change to the efficiency of the Southern Ocean as a carbon sink. This is a topic of vigorous debate (le Queré et al., 2007; Böning et al., 2008).

Although the maximum winter sea-ice extent in the Southern Ocean has increased slightly over the past 40 years, there have been significant changes to its regional distribution and seasonal duration (ACE CRC, 2009).

Temperature

A small change in temperature of the ocean requires a massive amount of heat compared to that required to warm the atmosphere, and the capacity of the oceans to store heat is very much greater than that of the atmosphere. Warming the whole atmosphere by 1 degree requires the same amount of energy as heating just the top three meters of the surface ocean by 1 degree. The ocean is so deep and, in some regions the currents so slow, that some waters have not seen the ocean surface for over 1000 years. These time-scales indicate that it may take centuries for changes in the surface ocean to be completely communicated throughout the depth of the ocean. Nonetheless, significant changes in Southern Ocean temperatures are being observed at all depths.

Since 1992 the observed average warming in the upper 400 m of the ocean around the globe near 40°S has been much greater than the globally averaged upper ocean warming over this period (Willis et al., 2004). This increase in temperature causes thermal expansion of the water column, and sea-level rise in this region is one of the highest seen on Earth. In the upper 700 m of the Southern Ocean an increase of 0.2°C has been observed since the early 1960s (Dominiques et al., 2008). This warming is largely due to changes in the near-surface layers north of the ACC. Warming of Mode Water is observed and is thought to be due to warmed surface waters from south of the ACC sinking into the ocean interior at about 40°-50°S (Wong et al., 2001; Aoki et al., 2003). In the Indian and Western Pacific sectors of the Southern Ocean, warming has been observed where deep water upwells in the lower limb of the overturning circulation, between about 50°S and 60°S (Aoki et al., 2005a, Böning et al 2008), Figure 3 .

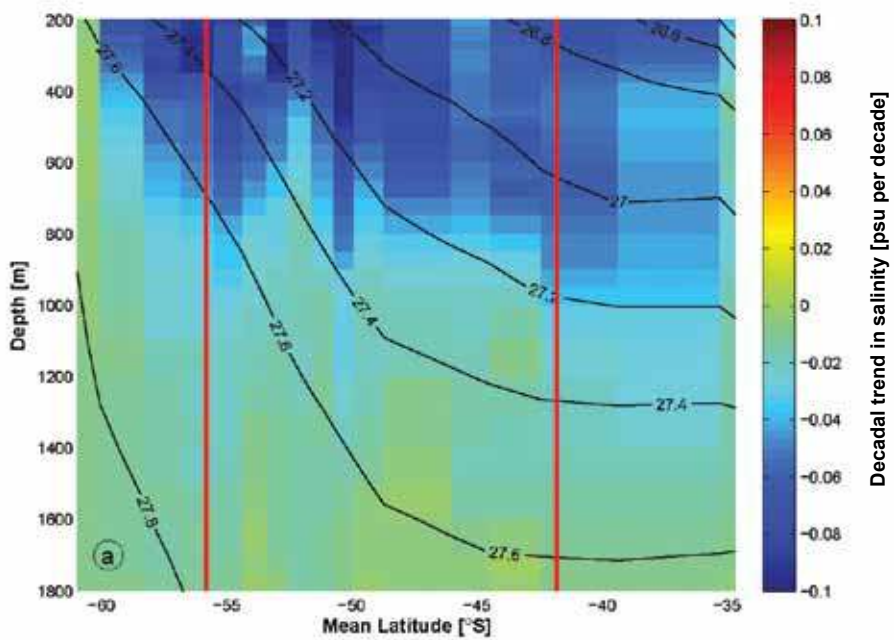
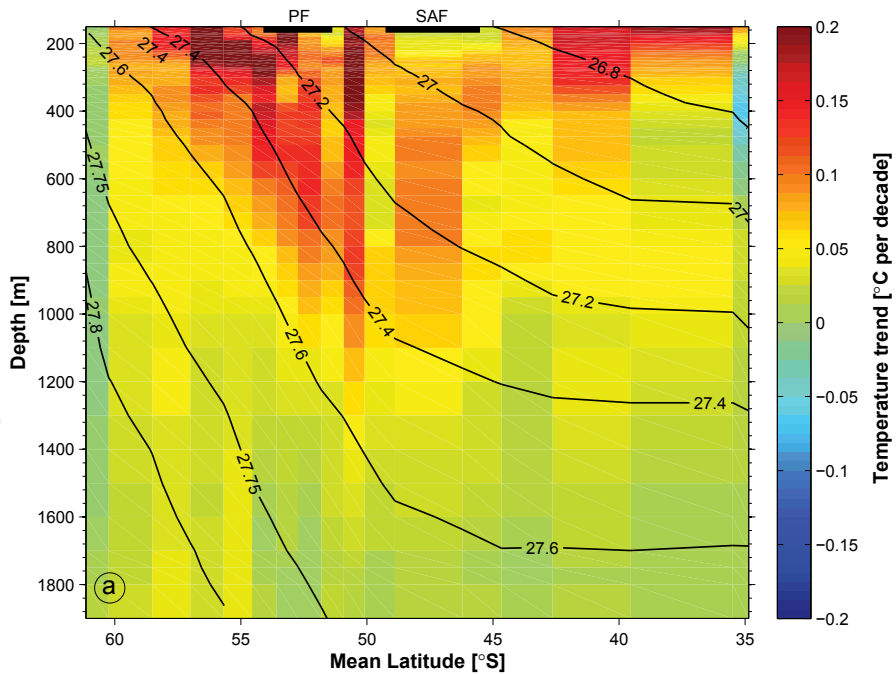


Figure 3. Top: Mean decadal trend of potential temperature in the Southern Ocean. Black lines are density contours (isopycnal surfaces). **Bottom:** Mean decadal trend of potential salinity in the Southern Ocean. (Böning et al., 2008)

The mid-depth waters of the Southern Ocean have also warmed. Near 900 m temperatures increased from the 1950s to the 1990s throughout most of the Southern Ocean (Aoki et al., 2003; Gille, 2002). The largest changes are found in the main part of the ACC, where the warming at 900 m is up to 0.5°C and is similar in magnitude to the increase in regional surface air temperatures. This large ocean warming reflects both a southward shift of the ACC and water-mass changes driven by changes in surface forcing, consistent with predictions of a warming climate (Böning et al., 2008, Mieijers et al., 2011).

Making scientific measurements in the ocean is not a simple task, and until recently there was a paucity of observation in the Southern Ocean compared with elsewhere. Robotic oceanographic instruments ("Argo floats") have dramatically improved the observational coverage of the upper 2 km of the Southern Ocean. These observations, combined with measurements from ships and satellites, show the Southern Ocean as a whole has warmed in recent decades. Overall, the Southern Ocean shows significant changes in heat content, although differences between regions (Heywood et al., 2009) can complicate the detection of longer-term trends. These Southern Ocean heat content changes show the importance of the overturning circulation for transferring ocean surface changes towards the equator and into the deep ocean.

The very deep Antarctic Bottom Water has also warmed (Johnson and Doney, 2006a,b; Johnson et al., 2007; Purkey and Johnson, 2010).

Salinity

Changes in rain (and evaporation) above the ocean cause changes in ocean salinity and hence changes in the density of surface waters. Intermediate Water north of the ACC (Figure 2) has been freshening since the 1960s (Wong et al., 1999; Bindoff and McDougall, 2000; Helm et al, 2010). Freshening of Atlantic Intermediate Water has also been observed (Böning et al, 2008, Figure 3) and new observations of Southern Ocean salinity show that surface and deep waters have also freshened (Aoki et al., 2005a; Durrack and Wijffels, 2009).

Around Antarctica there is also growing evidence of reduced salinity of the Antarctic Bottom Water (Aoki et al., 2005b; Rintoul, 2007). For example, Figure 4 shows freshening observed at several locations along the flow path of Antarctic Bottom Water between the late 1960s and 2005. These observations of freshening are important because they are consistent with increased precipitation over the Southern Ocean and with increased melt rates of the Antarctic ice sheet. Faster melting of glacial ice in Antarctica will drive more rapid rise in sea level.

Ocean circulation

Over the past 15 years, the ACC has moved southward. Using satellite measurements of sea-surface height, and the relationship between that and subsurface water-mass properties, the variability of the ACC can be determined for the past 15 years with a spatial resolution of about 100 km. Over that time the main front of the ACC has moved progressively southwards (Sokolov and Rintoul, 2009b) (Figure 5). This southward

movement also implies an increase in heat content and a freshening of upper waters, and has been attributed to the southward shift and increased intensity of the Southern Hemisphere westerly wind regime (Cai, 2006; Downes et al., 2009).

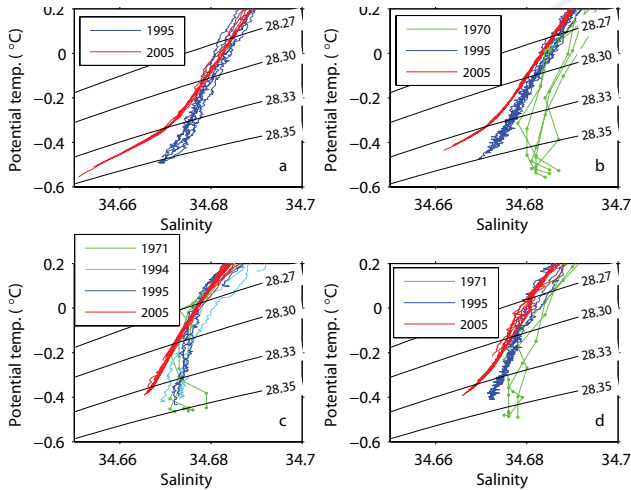


Figure 4. Potential temperature (vertical axis) and salinity (horizontal axis) diagrams showing freshening of bottom water in the Australian Antarctic Basin. Labelled black lines are density contours: AABW is defined to be water denser than 1028.27 kg per m³. The four plots are for different location on the flow path of AABW spreading northward: **(a)** over the Antarctic continental rise at 115°E; **(b)** north of the continental rise at 115°E; **(c)** near 65°S, 80°E, in the Princess Elizabeth Trough; **(d)** east of the Kerguelen Plateau near 55°S, 100°E. (Rintoul, 2007).

The Southern Ocean overturning circulation is driven by differences in the density of seawater. A reduced salinity decreases the density of the water and these less dense surface waters do not sink as effectively, thereby weakening the overturning circulation. The freshening of Antarctic Bottom Water illustrated in Figure 4 can be traced back to changes in the source regions of this water mass, including the Ross Sea where measurements show a steady decline in salinity over the past four decades (Jacobs et al., 2002). So far, there is no evidence of a change in the strength of the deep overturning circulation in the Southern Ocean, but the observed changes in deep water properties illustrate how the signals of climate variability and change at high latitudes can be quickly transferred to the deep ocean.

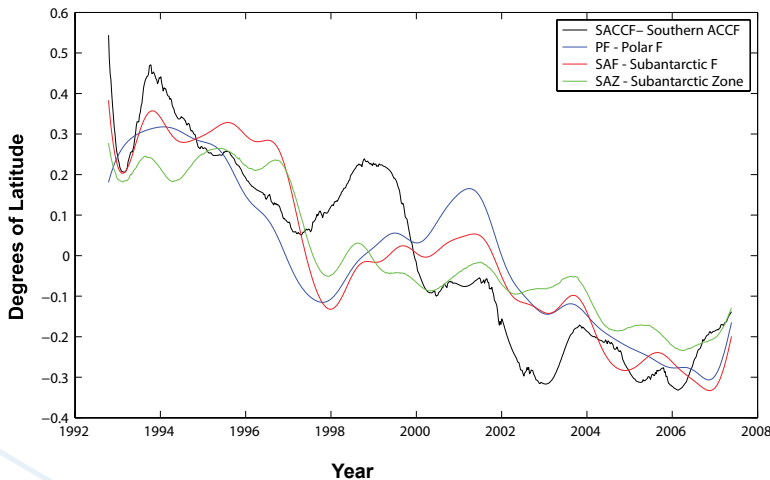


Figure 5. Satellite altimeter measurements of the displacement of the Southern Ocean sea surface height (SSH) between 1993 and 2007 at Southern Ocean frontal zones (see Figure 1 for the location of these). The decrease in SSH in these zones is a result of a southward shift of the Antarctic Circumpolar Current (Sokolov and Rintoul, 2009b).

Carbon uptake by the oceans

The ocean and the terrestrial ecosystems absorb roughly equal fractions of the CO₂ emitted by human activity that does not remain in the atmosphere. However there is evidence that the fraction taken up by the global ocean has decreased from $42 \pm 7\%$ between 1750 and 1994, to $37 \pm 7\%$ between 1980 and 2005 (Bindoff et al., 2007). This decrease is consistent with the rising CO₂ concentration but the decrease is only just significant. At the same time, the cumulative absorption of CO₂ has altered ocean chemistry and increased the ocean acidity, with potentially serious impacts on ecosystems (ACE CRC, 2008). The pH of the surface ocean has already been computed from observations to have decreased by 0.1 pH units (equivalent to a 26% increase of hydrogen ions) since pre-industrial times (Sabine et al., 2004; Raven et al., 2005).

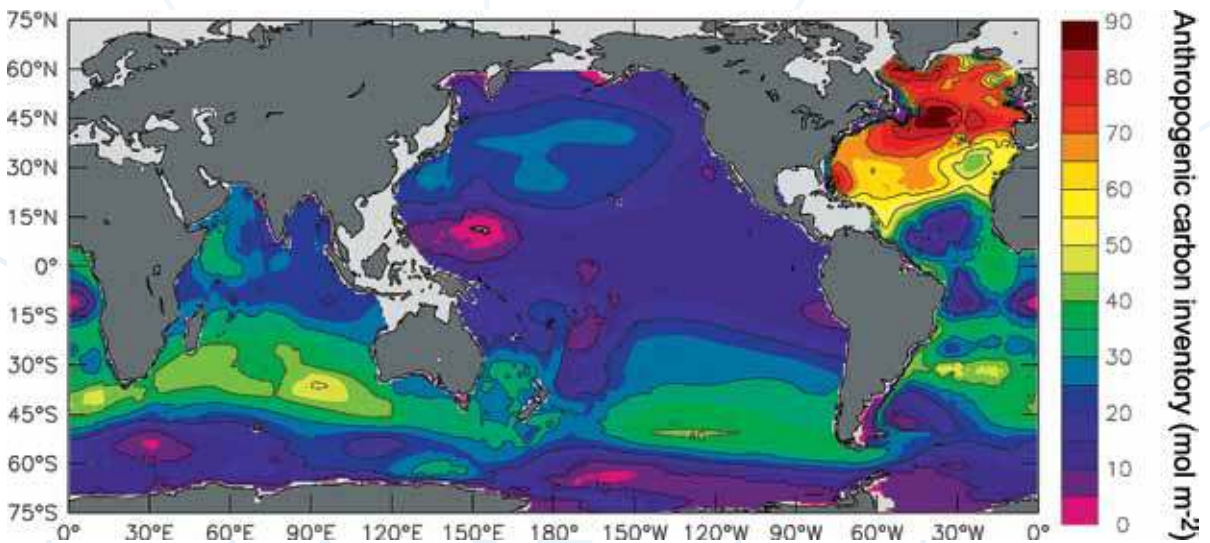


Figure 6. The global uptake of anthropogenic carbon from 1750 to 1985 by the oceans. The largest cumulative uptake of anthropogenic carbon since pre-industrial times is in the Northern Atlantic (top right corner) and the mid-latitude Southern Ocean (between about 30°S and 50°S) (Bindoff et al., 2007).

The distribution of anthropogenic carbon in the ocean shows a striking spatial pattern. The two regions that have the highest anthropogenic carbon content are the North Atlantic and the Southern Ocean (Figure 6). The distinctive circumpolar band of high anthropogenic carbon content at between 30°S and 45°S is associated with the subducting waters which are part of the upper limb of the overturning circulation. South of this circumpolar band is a region of lower anthropogenic carbon content which corresponds to the much older upwelling waters that have not recently been in contact with the atmosphere.

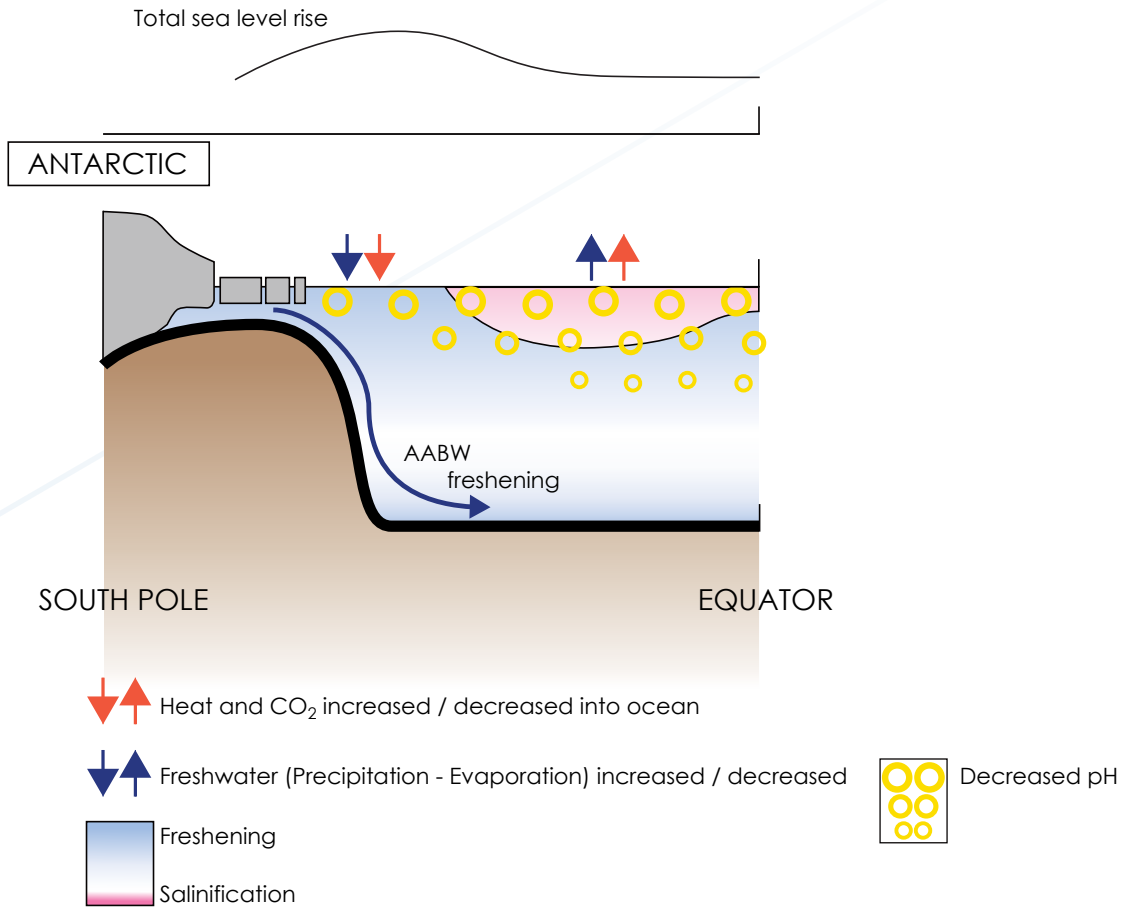


Figure 7. Observed changes in the Southern Ocean, including ocean temperature and salinity (adapted from Bindoff et al., 2007).

There is also some evidence that the efficiency of the Southern Ocean as a carbon sink may be declining. If the overturning circulation in the Southern Ocean is constant, then an increase in the concentration of CO₂ in the atmosphere will drive greater CO₂ across the ocean surface, and the total uptake of CO₂ by the ocean should also increase. However, based on atmospheric observations and modelling, Le Quéré et al. (2007) have suggested that the relative rate at which the Southern Ocean is absorbing CO₂ has decreased because of a southward shift of the westerly winds. Le Quéré et al. (2007) estimate from a model that in the two decades up to the year 2000 there was approximately a 30% decline in the Southern Ocean's capacity to absorb CO₂. This suggestion has been challenged by several other investigators (Boning et al, 2008; Law et al., 2008) and is an active area of research.

The Southern Ocean changes in temperature, salinity and acidity are summarised schematically in Figure 7.



"The main workhorse for oceanographers is the "CTD profiler", being deployed here in the deep blue waters off the continental shelf of Antarctica. CTD stands for conductivity (from which salinity is calculated), temperature and depth. During a voyage, the ship stops at the sampling location and the CTD is lowered on a thin cable from the surface to the sea floor and back, a round-trip of up to 10 km. The CTD collects continuous profiles of ocean properties and also collects water samples to be returned for analysis on the vessel."

Dr Steve Rintoul, Oceans Program Leader

FUTURE CHANGES IN THE SOUTHERN OCEAN

Climate models indicate that the Southern Ocean will continue to change in response to greenhouse warming, resulting in further ocean warming and freshening, higher sea level, less sea ice and changes in ocean currents. Some of these changes may amplify feedbacks in the climate system and increase the rate of climate change. Comparison of these model simulations with the observed changes at the end of the 20th century shows that the models closely match the observed changes across a broad suite of measures.

The present and projected trend of surface warming taking place over the Southern Ocean is however smaller than in other ocean regions because much of the heat is stored in the layers below. All of the models used by the IPCC (for a mid-range CO₂ emission scenario, A1B) show that the surface of the Southern Ocean has a low probability of warming in summer months by more than 2°C above the pre-industrial temperature by 2100 (Figure 8). Global average surface warming of 2°C above pre-industrial levels is regarded as a threshold indicator of dangerous climate change (Figure 8).

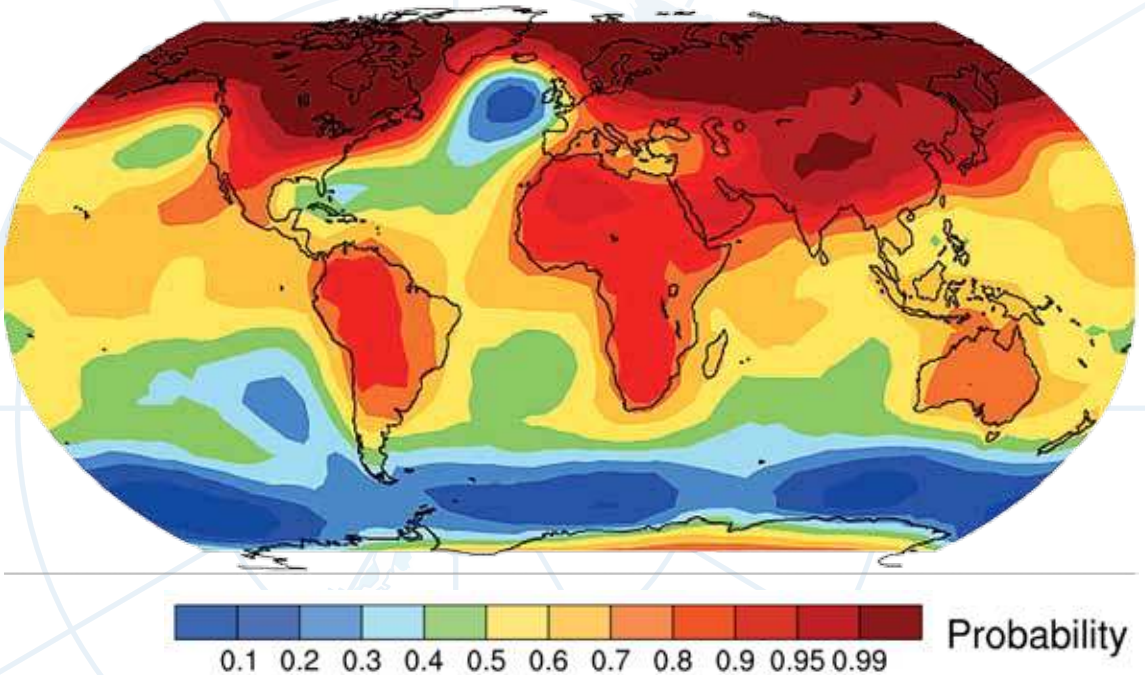


Figure 8. The probability of the mean surface temperature changing by more than 2°C in the period 2080 to 2099 relative to the period 1980 to 1999 for the December-February months (i.e. Southern Hemisphere summer). This probability was estimated from an ensemble of multiple climate models from the Fourth Assessment of the IPCC and is for a mid-range CO₂ emission scenario (A1B) (Meehl et al., 2007).

While Southern Ocean surface waters warm more slowly than other parts of the globe, large amounts of heat and carbon are transferred into the deep ocean by the Southern Ocean overturning circulation. As a result, the deeper waters of the Southern Ocean are warming more rapidly than in other oceans.

Climate models predict that the deeper waters of the Southern Ocean will warm faster than in any other ocean region, except for the northern North Atlantic. The relatively rapid and deep redistribution of heat within the ocean is also causing the Southern Ocean to expand and therefore contribute to regional sea-level rise. Estimates of thermal expansion of the ocean by 2100 are largest in the Southern Ocean (Meehl et al., 2007).

Future patterns of rainfall are also projected to change over the Southern Ocean, particularly south of 42°S (Meehl et al., 2007). Increased rainfall means that the surface and Intermediate waters will freshen. Mode waters are also affected by the changing precipitation and, when combined with the warming of the surface ocean, the strength of the down-welling limb of the overturning circulation could become weaker (Downes et al., 2009).

The increased absorption of atmospheric CO₂ into the oceans also makes the oceans more acidic. The average surface alkalinity of the global ocean is projected to decrease by 0.3 to 0.4 pH units by 2100. Increasing acidification is not limited to the surface of the ocean. Through the overturning circulation of the Southern Ocean the acidified waters are transported in to the ocean interior, affecting carbonate concentration throughout much of the water column.

As the oceans become more acidic, the number of carbonate ions decreases and this can adversely impact marine organisms that have shells made from calcium carbonate (calcite or aragonite). Evidence already exists that the relatively small observed decreases in carbonate concentration have significant impacts on shell sizes and weight of some marine species (Moy et al., 2009). This is discussed in more detail in ACE CRC (2008).

KEY SCIENCE, RESEARCH AND POLICY QUESTIONS

The Southern Ocean is changing, but the full extent of the changes and their implications are not yet well understood. Because the Southern Ocean plays a large role in the global climate system, and therefore in climate change, any long-term changes in the Southern Ocean will have both regional and global impacts.

Long-term and sustained observations of the physical and chemical properties of the Southern Ocean, from the surface to the abyssal depths, are crucial to charting and understanding Southern Ocean change. Access to satellite and other remote observations of the ocean surface; ship-based measurements; and the use of new technologies such as Argo floats and underwater autonomous vehicles, are essential components of integrated observations of the Southern Ocean; as is the ability to contribute to and maintain long-term observations and data sets.

The key research questions are:

- What are the causes of changes that have been observed in the Southern Ocean?

It is not possible to attribute with certainty the cause of observed changes in the Southern Ocean. Natural variability, enhanced greenhouse gas concentrations and the impact of ozone depletion on Southern Hemisphere atmospheric circulation may all play a role. Being able to observe changes and identify their causes is an important part of understanding climate change. Long-term observation of the Southern Ocean will be critical to answering this question.

- How will changes in Southern Ocean circulation, including the overturning circulation, affect global ocean temperature and the uptake of heat by the oceans?

Through its capacity to store heat the Southern Ocean plays a significant role in retarding warming in much of the Southern Hemisphere. However, ocean stratification is likely to increase implying a reduced rate of ocean heat uptake. Such a change could mean a faster increase in Southern Hemisphere ocean temperature than is currently projected. Changes in Antarctic Bottom Water production as a result of changes in circulation or sea-ice formation will have major consequences for global ocean circulation and climate.

- Will the rate of carbon uptake by the Southern Ocean reduce in the coming century?

There is evidence of declining efficiency in the uptake of CO₂ by the Southern Ocean, but there is presently no reliable prediction or modeling of future carbon uptake. A long-term reduction in the efficiency of the Southern Ocean carbon sink will have serious implications for the amount of CO₂ in the atmosphere. This decrease in uptake efficiency will in turn have a direct impact on the effectiveness of mitigation measures taken to meet temperature thresholds such as those set under the United Nations Framework Convention on Climate Change (e.g. +2°C by 2100). (The ACE CRC Position Analyses: CO₂ Emissions and Climate Change: Ocean Impacts and Adaptation Issues; and Ocean Fertilisation: Science and Policy Issues; and the ACE CRC Report Card: Southern Ocean Acidification (Refs) address some of the issues associated with CO₂ and the oceans.)

- To what extent will a warming Southern Ocean increase the melt of the Antarctic ice sheet and hence contribute to sea-level rise?

Recent research shows that the circulation of warmer ocean waters beneath floating ice shelves causing thinning by basal melt could be a significant

contributor to accelerated discharge of grounded ice from Antarctica, and from the west Antarctic in particular. The enhanced melt of Antarctic ice shelves is also a source of fresh water that will reduce the surface density of the Southern Ocean and contribute to changes in the overturning circulation and to ocean salinity.

- What are the likely climate feedbacks due to changes in ocean temperature, circulation or sea-ice extent?

The potential contribution of feedbacks to climate change in the Southern Ocean are largely unquantified and in some cases are not included in coupled models of the ocean-atmosphere system. These potential feedbacks include:

- regional changes in the spatial and temporal distribution of sea ice as a result of a warming ocean and atmosphere which in turn provides less albedo and therefore increased ocean surface warming;
- ocean warming causing basal melting from floating ice shelves, with consequent increased discharge of grounded ice that feeds into them and enhanced sea-level rise;
- increased ice melt producing less saline water, which in turn reduces the strength of the global overturning circulation.

Continued observations in the Southern Ocean, and incorporation of these observations into ocean and climate models, will be an important contribution to better understanding global climate change.

- How will changes in the surface temperature of the Southern Ocean alter weather patterns such as rain and winds over Australia?

Weather patterns over southern Australia are influenced by the atmosphere and ocean south of Australia, but it is not yet understood how changes in Southern Ocean surface temperatures might influence rainfall and temperature over Australia. Better resolving these changes will contribute to more accurate climate change projections at global and regional scale.

STRATEGIC FOCUS FOR SOUTHERN OCEAN RESEARCH

Australia is strategically placed geographically, politically and economically to make a substantial contribution to understanding climate change in the Southern Ocean, and our research in the region is highly regarded.

Given the critical role of the Southern Ocean in global and regional climate, important policy questions arise. What role should Australia play in gaining a better understanding of changes in the Southern Ocean and the implications of these changes for climate change? What are the priorities for investment in research? How should Australia respond domestically to predicted changes in the Australian region, including, for example, projections of sea-level rise? What are the implications for the sustainability of ecosystems and fisheries in the Southern ocean, including the world's largest underexploited fishery, the krill fishery?

Part of the strategy to address these challenges will be to invest in and exploit the current revolution in ocean observations - robotic instruments such as Argo floats, underwater autonomous vehicles, satellites and instrumentation that can automatically record information while ships and planes are under way across the oceans (Figure 9).

There should be a specific focus on better understanding the overturning (or thermohaline circulation) through deployment of instruments that can gather data on the physical and chemical properties of the ocean at great depth.

Access to 'bluewater' research vessels that can operate in the Southern Ocean¹, and access to ice-breaking research vessels that can operate in ice-covered waters around the Antarctic continent is crucial to succeeding in this critical research.

Given its location and capabilities, Australia should provide a leadership role in the development and implementation of the planned Southern Ocean Observing System (SOOS) and other important international research efforts in the Southern Ocean.



¹ The Australian Government is funding the construction and operation of a bluewater marine research vessel which will have the ability operate in tropical and temperate waters and to the edge of the sea-ice zone. Aurora Australis, Australia's ice-breaking research vessel, is approaching time for replacement or major refit. Australia's bluewater research capability is modest by international standards.

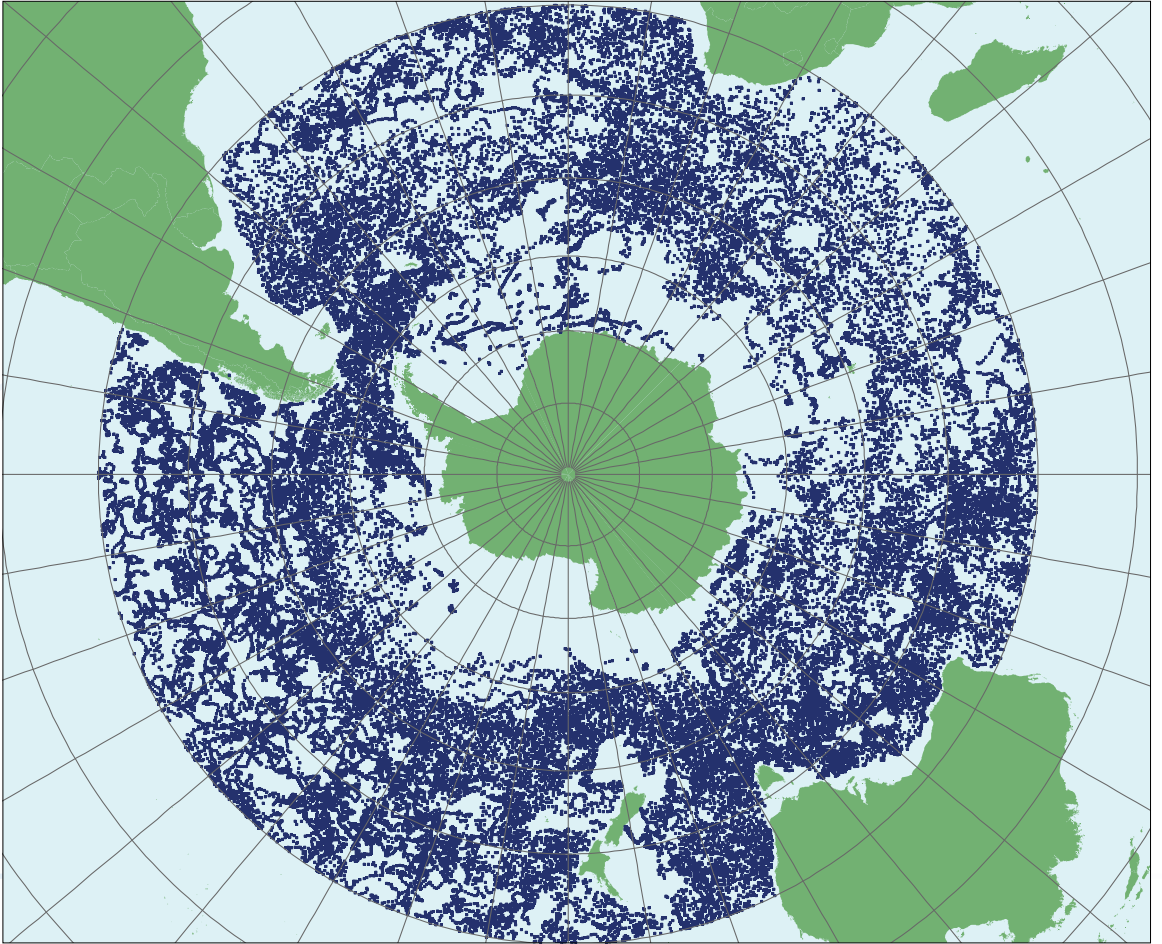


Figure 9. Example of the Argo float coverage required for SOOS. During the intensive International Polar Year observing period (March 2007 – March 2009), 61,965 profiles of temperature and salinity were collected in the Southern Ocean by 1353 Argo floats. (Base map: M. Belbeoch, Argo Information Centre, JCOMMOPS)

MERTZ CALVING HIGHLIGHTS THE VALUE OF MULTI-DISCIPLINARY RESEARCH

Improvements to the Southern Ocean observing system will require extensive international collaboration such as that demonstrated during the International Polar Year between March 2007 and March 2009. During this intensive two-year observation period, different nations undertook 12 coordinated deep-water oceanographic transects which made full-depth measurements of temperature, salinity, oxygen and a broad suite of chemical tracers across the Southern Ocean. They also undertook 20 shorter transects across the continental shelf around Antarctica. Together with more than 60,000 temperature and salinity profiles measured with robotic floats during the same period, these observations provided a detailed "snapshot" of the status of the Southern Ocean.

But if the right scientific resources are available, important observations can also be gathered when opportunities arise. For example, in February 2010 a massive iceberg calved from the Mertz Glacier in the Australian Antarctic Territory, a region of significant Bottom Water formation. The iceberg, 78 kilometres long with a surface area of 2,500 square kilometres, broke off the Mertz Glacier after being rammed by another iceberg.

At short notice, a multi-disciplinary team of Australian scientists, led by ACE Oceans Program Leader Dr Steve Rintoul, organised a voyage to investigate the impacts of this unique event. This voyage to the Mertz region was undertaken in the summer of 2010/11 on the ice-breaker *Aurora Australis*. The iceberg calving allowed the team to reach and study areas of the continental shelf that were previously inaccessible. These included the area formerly covered by the glacier tongue, as well as a large area to the east that was covered by thick, impenetrable, multi-year sea ice until the calving event.

A preliminary analysis of measurements suggests that the calving of the glacier tongue has had an impact on the salinity of dense water on the continental shelf. The dense waters sampled in 2010/11 were much fresher and less dense than samples taken at the same locations three years earlier. The surface waters were also much fresher than in 2008.

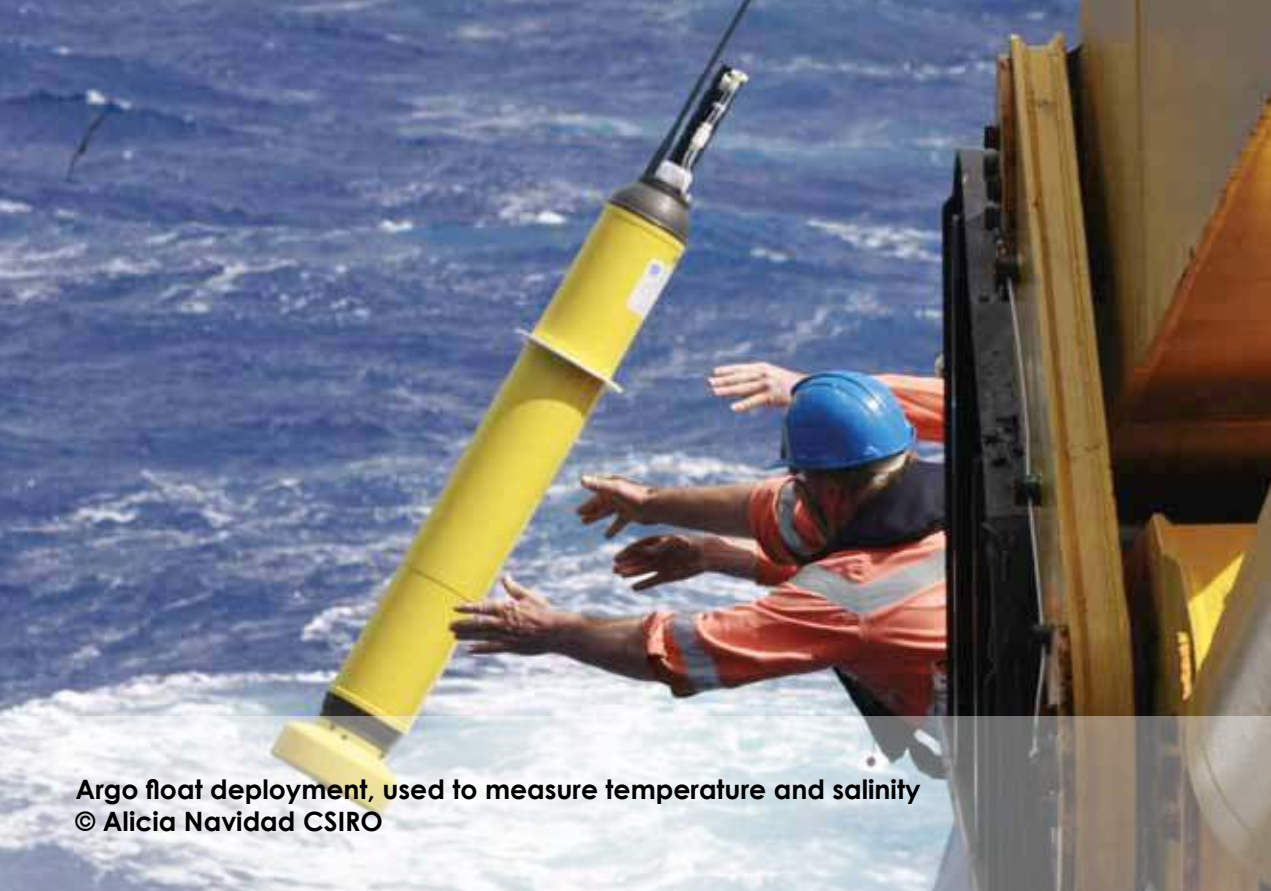
Antarctic and Southern Ocean science is logistically difficult and expensive, and international collaborations are important in ensuring that critical research is carried out in a coordinated and effective way. Australian research efforts are part of integrated international programs and collaboration with scientists from a range of countries gives significant leverage to Australia. Being able to maintain these international collaborations and instigate and shape international research efforts is an important national interest consideration.

Australia has a unique dependence on Southern Ocean processes and is well positioned scientifically and geographically to contribute to resolving current uncertainties in our understanding of climate change. To do this requires the ability to bring together observations and models so that the causes of the observed changes can be clearly detected and attributed. Society needs access to this predictive capacity in order to be informed about the changes that have already occurred, that are occurring now and that are projected to occur in the future.

While these challenges are large, there is a revolution under way in the capability of observation systems, in communication systems and in our capacity to model and simulate the atmosphere, oceans and ecosystems. These are the essential tools that now only need a greater degree of integration and interoperability to deliver the regular climate assessments and services to decision makers at all levels.

CONCLUSION

The Southern Ocean profoundly influences global and regional climate. Changes have already been observed in the Southern Ocean, but we are only beginning to describe and understand the extent and consequences of these changes. Supporting a strong, focused scientific effort on Southern Ocean change and maintaining the capacity for continued integrated observations and strategic research is vital to understanding global climate change and its impacts on Australia.



Argo float deployment, used to measure temperature and salinity
© Alicia Navidad CSIRO



Ocean glider about to be deployed © Eric Schulz Bureau of Meteorology



Polynya ocean monitoring © Steve Rintoul CSIRO



Autonomous Underwater Vehicle deployment, used for high-resolution imaging at depth @ Australian Centre for Field Robotics, University of Sydney

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