# Position Analysis

CAUSES AND CONSEQUENCES OF SOUTHERN OCEAN CHANGE

ANTARCTIC CLIMATE & ECOSYSTEMS
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**Position Analysis: Causes and Consequences of Southern Ocean Change**

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The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.

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**This document aims to:**

- To highlight recent advances in our understanding of Southern Ocean circulation and biogeochemistry and their influence on the rest of the globe.
- To document how and why the Southern Ocean is changing.
- To summarise present understanding of how the Southern Ocean will change in the future and the potential impacts on Australian and global climate, sea level, and marine ecosystems.

## Contents

# SUMMARY

The ocean influences the rate of climate change by storing and transporting vast amounts of heat and carbon dioxide: more than 93% of the extra heat stored by the planet over the past 50 years is found in the ocean, and about 30% of human emissions of carbon dioxide have been removed and stored by the ocean.

The Southern Ocean dominates the ocean uptake of anthropogenic heat and carbon dioxide (where anthropogenic refers to carbon dioxide released by human activities, and the warming that results from this). The unique circulation of the Southern Ocean transports surface waters, enriched in heat and carbon dioxide from the atmosphere, deep into the interior of the ocean. This so-called overturning circulation also returns nutrients to the surface layer, supporting phytoplankton growth.

Given the critical role of the Southern Ocean in the Earth's climate system, change in the region would have the potential to have widespread consequences. Changes have indeed been observed in many aspects of the Southern Ocean in the relatively well-measured period since 1970.

The Southern Ocean has warmed, freshened and become more acidic. In West Antarctica, more ocean heat is reaching

Warm water causes loss of ice from the Antarctic Ice Sheet.

floating ice shelves around the edge of the Antarctic Ice Sheet, driving more rapid melt and loss of ice. Measurements show that ocean heat content and ice loss from the Antarctic Ice Sheet have both accelerated in recent decades, causing an acceleration in sea level rise.

For other aspects of the Southern Ocean, the observational evidence for long-term trends is less clear. There is growing recognition that climate variability, including tropical climate phenomena like El Niño, has a signature in the Southern Ocean that may obscure gradual long-term changes. For example, recent studies have shown that the Southern Ocean carbon sink varies strongly from decade-to-decade.

While substantial uncertainties remain, recent advances provide a clearer view of future changes in the Southern Ocean and their consequences. The Southern Ocean will continue to warm, with the strongest warming on the northern flank of the Antarctic Circumpolar Current. The transport of warm water to the base of floating ice shelves is expected to increase, driving more rapid melting of floating ice shelves and loss of ice from the Antarctic Ice Sheet. This will freshen the surface layer of the Southern Ocean, with implications for stratification, ocean circulation, and biological productivity.

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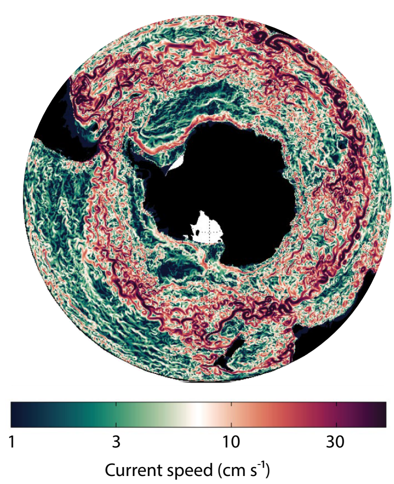
# ROLE OF THE SOUTHERN OCEAN IN THE EARTH SYSTEM

The Southern Ocean encircles Antarctica and extends northwards to the continents of the southern hemisphere. This vast expanse of ocean has a powerful influence on the earth system. This global influence arises from the unique system of ocean currents in the region, which in turn reflects the particular continental geography at high southern latitudes. The Southern Ocean is the only band of ocean that circles the earth, unblocked by continents.

This simple geographical fact has a profound influence on the global ocean circulation and therefore the climate of the earth. The world's largest ocean current is found in the Southern Ocean, the Antarctic Circumpolar Current (ACC), which flows from west to east around the Antarctic continent (Figure 1). By connecting the Atlantic, Indian and Pacific basins, this current system allows a global ocean circulation to exist.

Even more important, the Southern Ocean provides a window to the deep sea. The ocean is stratified, with light water near the surface and denser water below. But the light and dense layers are not flat. The layers are tilted by ocean currents, and the stronger the flow, the steeper the tilt. The deep, strong flow of the ACC is sufficient to tilt the layers of light and dense water by 1,000s of metres over the extent of the current (Figure 2). As a result, the Southern Ocean is the only part of the global ocean where deep layers of the ocean rise to the surface and interact directly with the atmosphere. Where ocean waters rise to the sea surface, they can exchange heat and carbon dioxide with the atmosphere. The upwelling of deep waters is balanced by sinking of surface waters. Where the surface waters sink to the deep ocean, they transfer heat and carbon dioxide into the ocean interior. The rising and sinking limbs are connected in the Southern Ocean to form an overturning circulation that extends throughout the global ocean.

**FIGURE 1:**
The strong, deep-reaching Antarctic Circumpolar Current flows from west to east around the Antarctic continent, connecting the major ocean basins. The current consists of multiple narrow filaments or jets, which go unstable and produce eddies, as illustrated in this snapshot of surface currents from a high-resolution numerical simulation (from Patara et al., 2016).



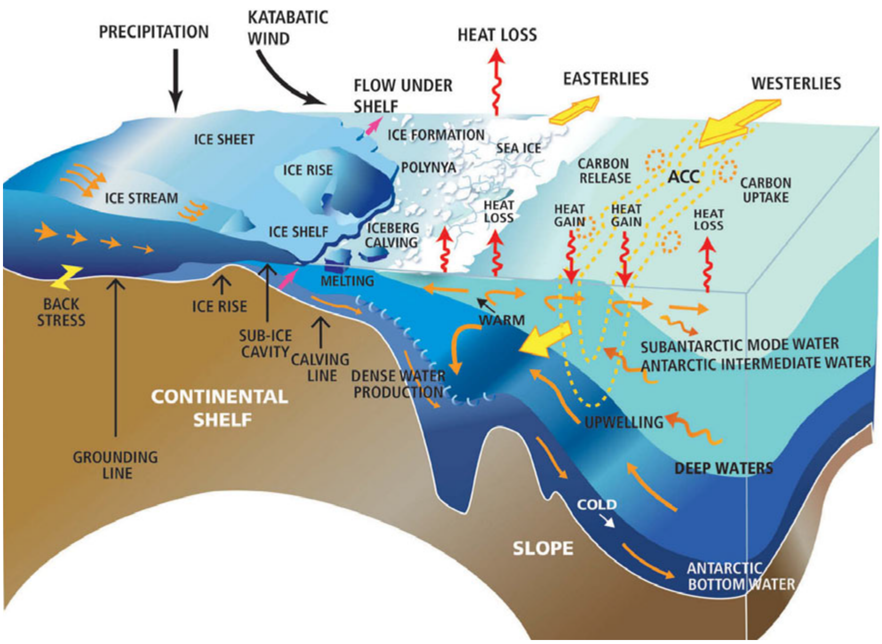



**FIGURE 2:**
A sketch of the three-dimensional circulation of the Southern Ocean and its interactions with the atmosphere and cryosphere. (National Research Council, 2011).

The global overturning circulation is central to the earth's climate. The oceans store and transport vast amounts of heat, carbon dioxide and other properties that influence climate. More than 93% of the extra heat energy stored by the Earth since 1970 is found in the oceans (Rhein et al., 2013). Likewise, about 30% of human emissions of carbon dioxide have been absorbed and stored by the ocean (Rhein et al., 2013). In this way, the oceans have slowed the pace of climate change that would have otherwise occurred. The overturning circulation is largely responsible for the uptake and storage of heat and carbon dioxide in the ocean.

The Southern Ocean dominates this uptake of heat and carbon dioxide. Of the extra heat and carbon dioxide added by human activities and stored by the ocean, more than 75% of the heat, and 40% of the carbon dioxide entered through the Southern Ocean (Frölicher et al., 2015). The vigorous overturning circulation in the Southern Ocean acts like a conveyor belt sweeping heat and carbon absorbed by the surface ocean, first northwards and then downwards into the ocean interior. As a consequence, the extent to which the ocean slows or accelerates the pace of climate change depends to a large extent on processes at work in the Southern Ocean.

The sketch in Figure 2 illustrates the interactions between the ocean, atmosphere, cryosphere and biosphere in the Southern Ocean that influence the earth's climate, sea-level rise and biological productivity. Deep water spreads southwards across

Ocean currents interact with the cryosphere, both sea ice and ice shelves.

the ACC and upwells to the sea surface. Some of the upwelled water sinks again as cold, Antarctic Bottom Water that carries oxygen and carbon dioxide to the deepest layers of the ocean. The rest of the upwelled deep water is made less dense by warming and freshening at the sea surface while being driven north by the winds, ultimately sinking again to supply mid-depth layers north of the ACC. These two counter-rotating cells form the Southern Ocean overturning circulation that plays such a dominant role in ocean storage of heat and carbon dioxide.

Deep water north of the ACC is rich in carbon dioxide as a result of decomposition of organic material raining down from the sea surface. When the deep water upwells to the sea surface south of the ACC, some of the carbon is released to the atmosphere. Where water sinks from the surface to supply the mid-depth layers of the ocean, carbon is transferred from the atmosphere to the ocean. The balance between these “sources” and “sinks” of carbon dioxide determines the net contribution of the Southern Ocean to the carbon budget in the atmosphere. Climate model experiments indicate that this meltwater may drive a further drying of the Southern Hemisphere climate, including much of Australia, over and above the impact of greenhouse gas emissions (Bronselaer et al., 2018).

Ocean currents also interact with the cryosphere, both sea ice and ice shelves. Freezing of sea water in winter produces sea ice. During the freezing process, most of the salt in the sea water is left behind, enriching the salinity below the ice. This process is critical in the formation of the cold Antarctic Bottom Water that occurs near Antarctica and carries oxygen to (ventilate) the global abyssal ocean. When sea ice melts, freshwater is released, reducing the salinity and density of surface waters. This process is critical in the formation of the waters of intermediate density that ventilate the mid-depth layers of the ocean (Subantarctic Mode Water and Antarctic Intermediate Water in Figure 2).

As illustrated in Figure 2, the ocean also interacts with floating ice shelves around the margin of the Antarctic Ice Sheet. As ice flows off the Antarctic continent and reaches the sea, it starts to float, forming an ice shelf. The ice shelves stabilise the ice sheet by providing a force that resists the flow of ice off the continent, acting to "buttress" the ice sheet. If the ice shelves thin or weaken, they provide less buttressing and more ice flows off the continent to the ocean. Warm ocean waters reaching the underside of the floating ice shelves can drive melt, thinning and a reduction in buttressing. In this way, the ocean surrounding Antarctica influences the stability of the Antarctic Ice Sheet and its contribution to sea-level rise. At the same time, the inflow of glacial meltwater affects the ocean circulation, which may result in feedbacks that influence climate and biogeochemical cycles.

Ocean currents also influence the biology of the Southern Ocean. Biological productivity in the Southern Ocean is limited by the trace micro-nutrient iron. The overturning circulation brings iron- and nutrient-rich deep water to the sea surface, supporting phytoplankton growth. However, the system runs out of iron before all the nutrients are utilised. The "left-over" nutrients are exported to lower latitudes, where they support up to 75% of global primary production north of 30°S (Sarmiento et al., 2004). Changes in the overturning circulation and nutrient utilisation in the Southern Ocean can therefore impact biological productivity on global scales. Many other factors influence phytoplankton growth, including the availability of light, the presence or absence of sea ice, and predation by higher trophic levels. Changes in ocean properties and circulation can also affect these factors and therefore the structure and function of Southern Ocean ecosystems.

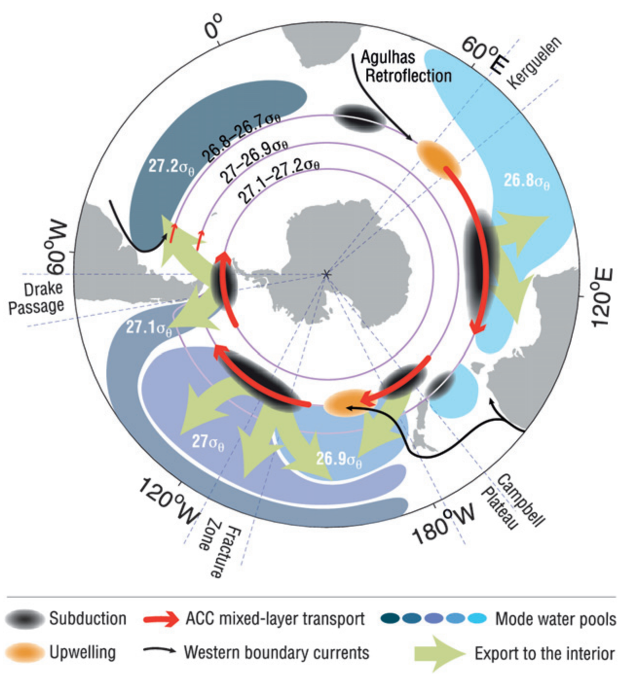
## RECENT ADVANCES IN UNDERSTANDING THE CIRCULATION AND DYNAMICS OF THE SOUTHERN OCEAN

The summary of the role of the Southern Ocean in the earth system articulated above has been built on progress made over the lifetime of the ACE CRC and its predecessors. Further advances in recent years have contributed to a new paradigm for the Southern Ocean circulation. While the circumpolar-average view illustrated in Figure 2 still holds, recent work by ACE CRC scientists and colleagues has clarified the pathways involved in the three-dimensional circulation of the Southern Ocean and the dynamics that govern them (Rintoul and Naveira Garabato, 2013; Rintoul, 2018).

The most significant shift in perspective is from a view in which the upwelling and downwelling associated with the overturning circulation occurs over the scale of ocean basins, to a recognition that both the rising and sinking limbs of the overturning are highly localised. The "subduction" of surface waters into the ocean interior occurs in "hot spots" set by interaction of the flow with the sloping base of the surface layer (Figure 3, Sallée et al., 2010). Carbon dioxide follows similar pathways into the ocean interior (Sallée et al., 2012). More recent studies show that the transport of carbon dioxide from the surface layer can be even more highly localised by small scale eddies and meanders of the ACC (Langlais et al., 2017).

The upwelling branch of the overturning circulation is also much more focused in particular locations than suggested

**FIGURE 3:** A schematic view of the pathways followed by surface waters as they sink into the ocean interior. The lighter pools of mode water are supplied by water that sinks in the Indian Ocean, with sinking of denser surface waters further east in the Pacific and Atlantic. The figure shows that the sinking limb of the overturning circulation is localised in particular regions, indicated by shaded black ovals (from Sallée et al., 2010).



by the circumpolar-average perspective that has dominated thinking about the Southern Ocean. By tracking millions of virtual particles in numerical simulations of the Southern Ocean, researchers have shown that the rising motion is concentrated in particular locations, closely associated with interaction of the flow with ridges on the sea floor (Figure 4; Tamsitt et al., 2017). The fact that the upwelling and downwelling branches of the overturning occur in particular locations, rather than being broadly-distributed across the Southern Ocean, suggests that the overturning circulation may be particularly sensitive to changes in the ocean at those locations. Given that the overturning dominates the uptake and storage of heat and carbon, these new insights into the dynamics of the circulation are of great importance for assessments of future climate change.

The fundamental role of bathymetry in shaping the three-dimensional pathways of the Southern Ocean circulation is now more fully appreciated (Figure 5; Rintoul, 2018). Interaction of the flow with sea floor bumps and ridges alters both horizontal and vertical motions. Eddy activity is enhanced downstream of topographic features. Eddies, in turn, transport heat, momentum, and other dynamical properties. As a consequence, vertical motion and cross-front exchange are enhanced in the lee of topography. Mixing is also enhanced where the flow interacts with topography.

RSV Aurora Australis making the first oceanographic measurements at the front of the Totten Glacier.

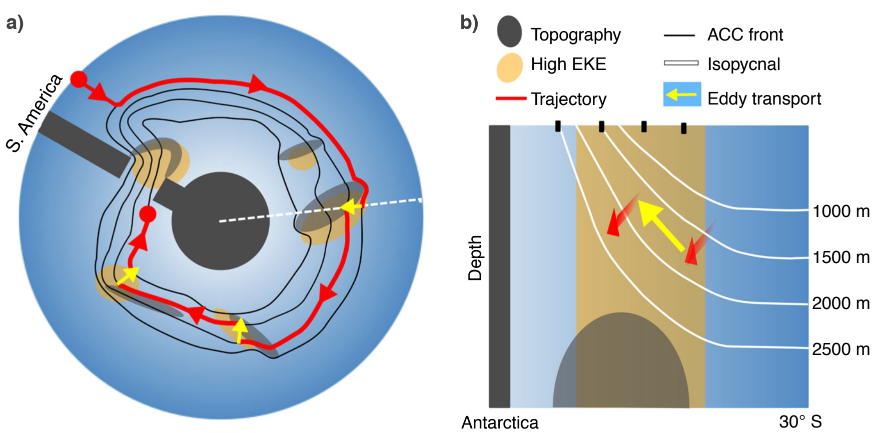
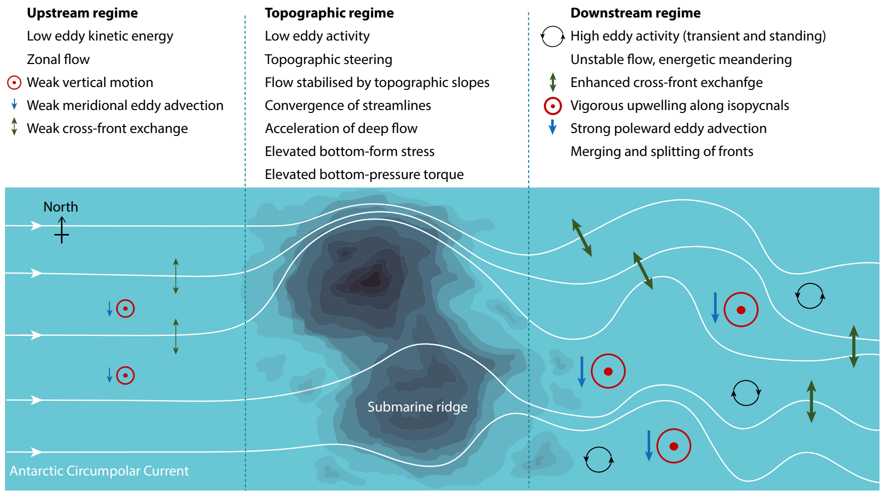



**FIGURE 4:** Idealised schematic illustrating how the upwelling limb of the Southern Ocean overturning occurs at topographic hotspots. (a) An idealised particle trajectory (red) follows streamlines (black) of the Antarctic Circumpolar Current (ACC). The trajectory crosses streamlines and upwells (yellow arrows) in regions of high eddy kinetic energy (EKE, yellow shading) at major topographic features (grey shading). This creates a southward and upward spiral as the particles shift southward and upward each time they encounter a topographic hotspot. (b) A two-dimensional vertical cross-section of the Southern Ocean from Antarctica to 30° S, indicated by the white dashed line in (a). White lines show idealised density layers shoaling and thinning toward the South (Tamsitt et al., 2017).

**FIGURE 5:** Interaction of the ACC with topography. The schematic illustrates the dynamical processes at work in the distinct dynamical regimes upstream, over ('topographic') and downstream of a topographic obstacle (represented by the shaded contours) in the path of the current. (Rintoul, 2018a).





The calving front of the Totten Glacier.

Recent research has highlighted the role of the ocean in controlling the future of the Antarctic Ice Sheet. In West Antarctica, new observations from ships and satellites have shown that changes in ocean currents and temperatures have caused an acceleration of melting of floating ice shelves (Paolo et al., 2015). As West Antarctic ice shelves have thinned and provided less resistance to the flow of the ice to the sea, loss of ice from the ice sheet has also accelerated (IMBIE, 2018). The Antarctic contribution to sea-level rise is now believed to likely be larger than estimated by the IPCC 5th Assessment Report.

New observations by the ACE CRC have provided further evidence of the potential vulnerability of the Antarctic Ice Sheet (Figure 6). East Antarctic ice shelves have long been thought to be more isolated from warm ocean waters than those in West Antarctica, and therefore the East Antarctic Ice Sheet was thought to be more stable. Given that more than 90% of the Antarctic ice volume is in East Antarctica, this was reassuring. However, an ACE CRC expedition in 2015 showed that at least some parts of East Antarctica are also exposed to warm ocean waters. The expedition was the first to reach the front of the Totten Glacier and collect oceanographic measurements. These showed that relatively warm water was flowing strongly into the ice shelf cavity through a deep trough at the front of the ice shelf (Figure 7, Rintoul et al., 2016). The warm water was melting the ice shelf rapidly from below, producing meltwater that was observed to be flowing out of the ice shelf cavity. The implication of the research is that estimates of future sea-level rise need to include the potential contribution from East Antarctica.

**FIGURE 6:** The Antarctic continent, with the Antarctic Ice Sheet removed. Areas shown in blue shading are below present-day sea level. Parts of the ice sheet sitting on bedrock below sea-level, known as marine-based ice sheets, are potentially vulnerable to melting by warm ocean waters and unstable retreat. ACE CRC scientists contributed to the discovery that much of the East Antarctic Ice Sheet was marine-based (Fretwell et al., 2013).

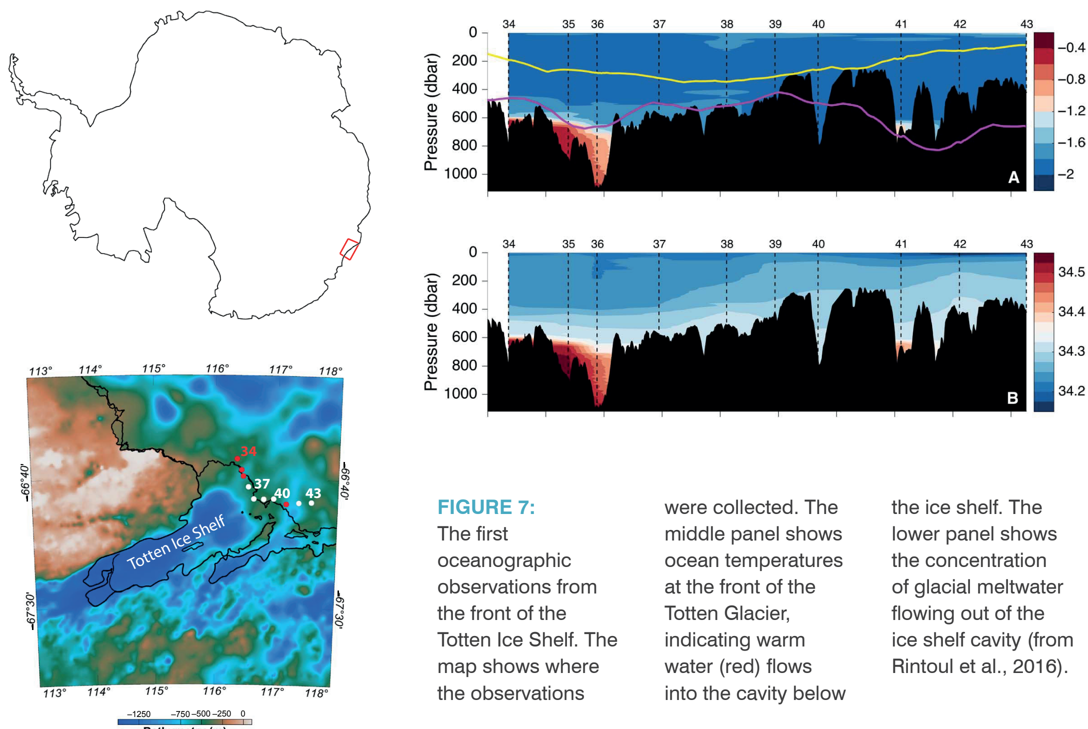



**FIGURE 7:** The first oceanographic observations from the front of the Totten Ice Shelf. The map shows where the observations were collected. The middle panel shows ocean temperatures at the front of the Totten Glacier, indicating warm water (red) flows into the cavity below the ice shelf. The lower panel shows the concentration of glacial meltwater flowing out of the ice shelf cavity (from Rintoul et al., 2016).

Antarctica lost 3 trillion tonnes of ice between 1992 and 2017 (IMBIE, 2018). In vulnerable West Antarctica, the annual rate of ice loss has tripled during that period, reaching 159 billion tonnes a year. Overall, enough ice has been lost from Antarctica over the past quarter-century to raise global sea level by 8 millimetres. The acceleration in loss of ice from Antarctica has been linked to increased melting of ice shelves by warm ocean waters. Research published by ACE CRC researchers shows loss of sea ice can also trigger ice shelf disintegration, by allowing undamped ocean swell to reach the front of the ice shelf and cause flexing of the ice shelf (Massom et al., 2018). These observations underscore the global impact of changes already underway in the Southern Ocean.

## RECENT CHANGE IN THE CIRCULATION OF THE SOUTHERN OCEAN

The Amundsen Sea is one of the few parts of the Antarctic margin where data exist that can be used to assess changes in ocean temperature in recent decades. These measurements confirm that water reaching the floating ice shelves has warmed in this region (Schmidtko et al., 2014). More recent studies have illuminated the processes controlling the delivery of ocean heat to the floating ice shelves (e.g. Jenkins et al., 2016). In particular, these studies have highlighted how tropical variability influences winds and therefore ocean currents and temperatures near Antarctica. The existence of strong teleconnections between the tropics and West Antarctica mean that tropical climate phenomena like El Niño and the Interdecadal Pacific Oscillation drive variability in ocean-driven melt of ice shelves on interannual and interdecadal timescales (Dutrieux et al., 2014; Jenkins et al., 2018). In other words, change in Antarctic and the Southern Ocean cannot be understood by studying this region alone.

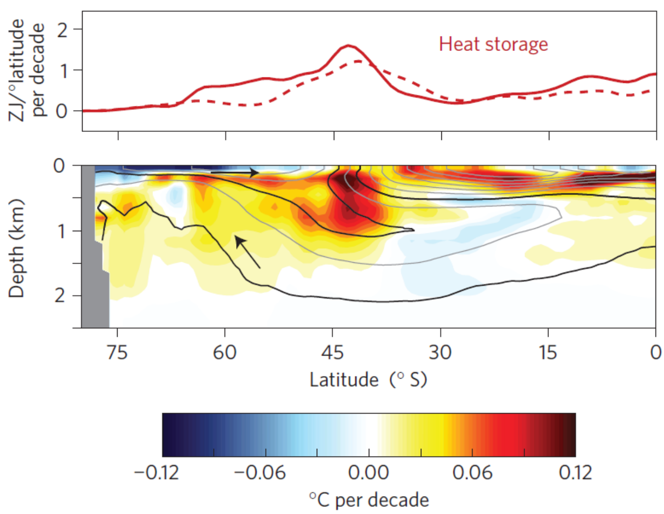



**FIGURE 8:** Change in ocean temperatures between 1982 and 2012, averaged along latitude circles in the southern hemisphere. Top: trend in heat stored by the ocean, from two different estimates (ZJ/decade). Bottom: trend in ocean temperature (°C/decade). The black contours show salinity. The arrows show the direction of the upper limb of the Southern Ocean overturning. The circulation sweeps heat to the north, where it accumulates north of the ACC, resulting in large trends in warming and heat storage. (Armour et al., 2016).

The Southern Ocean has warmed overall, but the warming is not uniform (Figure 8, Armour et al., 2016). The surface ocean close to Antarctica has actually cooled, despite warming of the overlying atmosphere. This surface cooling is in part caused by the release of fresh water from melting ice that can both cool the surface layer and warm the subsurface waters that access ice shelf cavities (Silvano et al., 2018; Bronselaer et al., 2018). On the other hand, north of the ACC the ocean has warmed, from the surface to depths of 1 to 2 km below the surface.

This surprising pattern of ocean change reflects the action of the Southern Ocean overturning circulation. Cold water upwells to the surface south of the ACC and, because it has been isolated from the atmosphere for a long time, is not yet affected by the warmer atmosphere. The portion of this water driven north by the winds is warmed by the atmosphere. North of the ACC, the water sinks again and carries the extra heat into the upper 1-2 km of the ocean. In this way, the upper limb of the overturning circulation acts like a conveyor belt sweeping heat north across the ACC and down into the ocean interior. Warming of the upper ocean north of the ACC has in fact dominated the total increase in ocean heat content in the past decade (the period that is well-measured by profiling Argo floats) (Roemmich et al., 2015). ACE CRC research has highlighted the processes responsible for this extra ocean heat storage (Gao et al., 2018).

The surface waters of the Southern Ocean have freshened in recent decades. New research has shown that sea ice melt has made a significant contribution to the observed freshening (Figure 9, Haumann et al., 2016). On average, sea

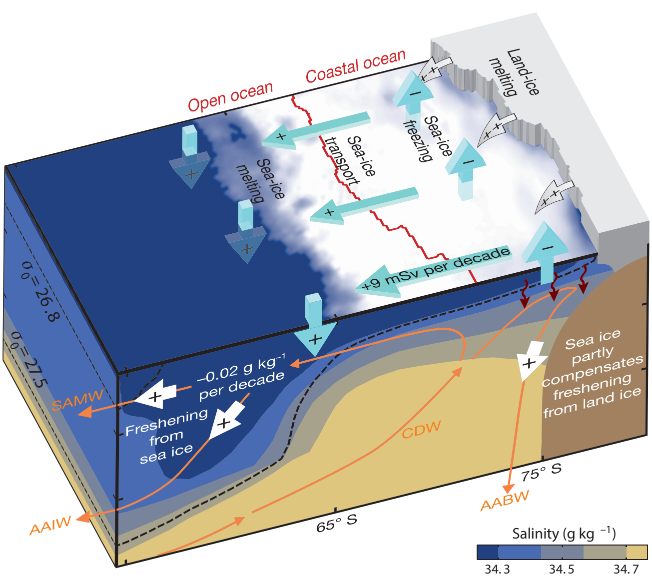
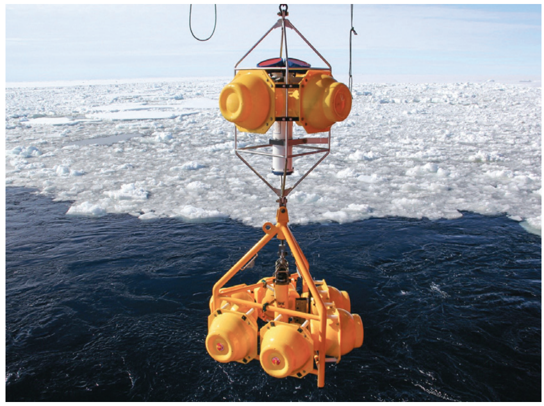



**FIGURE 9:**
Schematic illustration of the role of sea ice melt in driving recent freshening trends in the Southern Ocean. (Haumann et al., 2016).

Steve Rintoul



Steve Rintoul

**Left:** Throwing a grappling hook to recover a mooring in heavy sea ice in the Dalton Polynya.

**Right:** Mission accomplished: an oceanographic mooring coming back on board after measuring ocean currents, temperature and salinity, the first measurements spanning a full year from this part of the ocean.

ice is formed closer to Antarctica and melts further north. The northward transport of sea ice carries freshwater northward, which is released as the ice melts. This research demonstrates the importance of sea ice melt to the overturning circulation. Warming and the addition of freshwater both act to transform relatively dense deep water upwelling south of the ACC into the relatively light waters that sink north of the ACC. Work by ACE CRC researchers shows northward sea-ice movement also transports iron from coastal waters, which contributes to the formation of hotspots of phytoplankton productivity that can drive biological carbon uptake (Vancoppenolle et al., 2013; Schallenberg et al., 2018).

The trend towards stronger winds and warming and freshening of the surface ocean should have increased the strength of the upper overturning cell. However, changes in the strength of the overturning circulation are difficult to observe directly, because the flows are weak and occur over broad scales. Indirect evidence from measurements of dissolved gases do support an increase in the strength of the overturning circulation between the 1990s and early 2000s, associated with an increase in westerly winds (Waugh et al., 2012). But more recent work has shown a reduction in the most recent decade, highlighting variability in the overturning circulation, with important implications for heat and carbon storage by the ocean (DeVries et al., 2017).

In the deepest layers of the Southern Ocean, widespread freshening, warming and contraction of Antarctic Bottom Water have been observed over the past 30 to 50 years (Rintoul, 2007; Purkey and Johnson, 2010, 2012, 2013; van Wijk and Rintoul, 2014). The long time series of observations collected by the ACE CRC between Tasmania and Antarctica is one of the longest and most complete records of deep ocean change. ACE CRC research has shown that the primary driver of changes in bottom water properties is freshening in regions of dense water formation on the Antarctic continental shelf. The freshening, in turn, likely reflects an increase in melt of sea ice and glacial ice. The magnitude of the bottom water changes was a surprise; for example, south of Australia the volume of the Antarctic Bottom Water layer decreased by 50% between 1970 and the 2000s (Figure 10, van Wijk and Rintoul, 2014).

However, the most recent ACE CRC expedition to the area has revealed yet another surprise. After nearly 50 years of becoming less salty and less dense, an expedition in 2017 found that the salinity of newly-formed bottom water had rebounded to levels not seen since the mid-1990s. While the full explanation for the "rebound" is not yet clear, it is likely to reflect changes in meltwater input to the source regions south of Tasmania and in the Ross Sea.

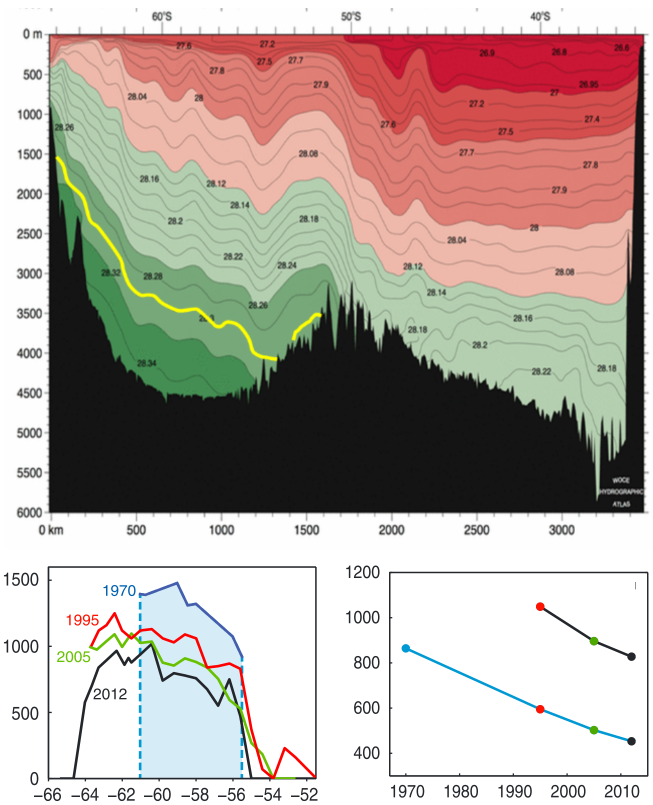



**FIGURE 10:** Contraction of Antarctic Bottom Water. The left plot shows the distribution of density along a transect between Perth and Antarctica (north to the right). The yellow line highlights a density surface that marks the top of the Antarctic Bottom Water layer. The plot on the upper right shows changes in the thickness of the layer as a function of latitude, showing how the layer has thinned between 1970 and 2012. The plot on the lower right shows the decrease in area of the layer over time. (van Wijk and Rintoul, 2014).

# RECENT CHANGE IN THE BIOGEOCHEMISTRY OF THE SOUTHERN OCEAN

The Southern Ocean inventory of anthropogenic carbon dioxide has increased, with the largest increased in ocean carbon storage occurring in mode and intermediate waters north of the ACC (Khatiwala et al., 2013; Le Quéré et al., 2017). This increase in carbon has reduced the pH of Southern Ocean waters. The carbon chemistry of surface waters varies with season, as phytoplankton take up carbon as they grow in summer. Over the next few decades the surface waters of the Southern Ocean will in winter become undersaturated with respect to aragonite, a form of calcium carbonate that is used by many organisms to form shells and other structures (McNeil and Matear, 2008; Kwiatkowski and Orr, 2017). Sinking particles carry carbon to the ocean interior, isolating it from the atmosphere. However, this ecosystem service is changing in response to recent circulation changes that have made particles susceptible to dissolution at shallower depths (Conde-Pardo et al., 2017). The magnitude of this impact depends on the amounts of carbonate forming organisms in the Southern Ocean, which recent ACE CRC surveys suggest are relatively low except in Subantarctic waters, contrary to expectations from satellite remote sensing (Trull et al., 2018).

Esmee van Wijk

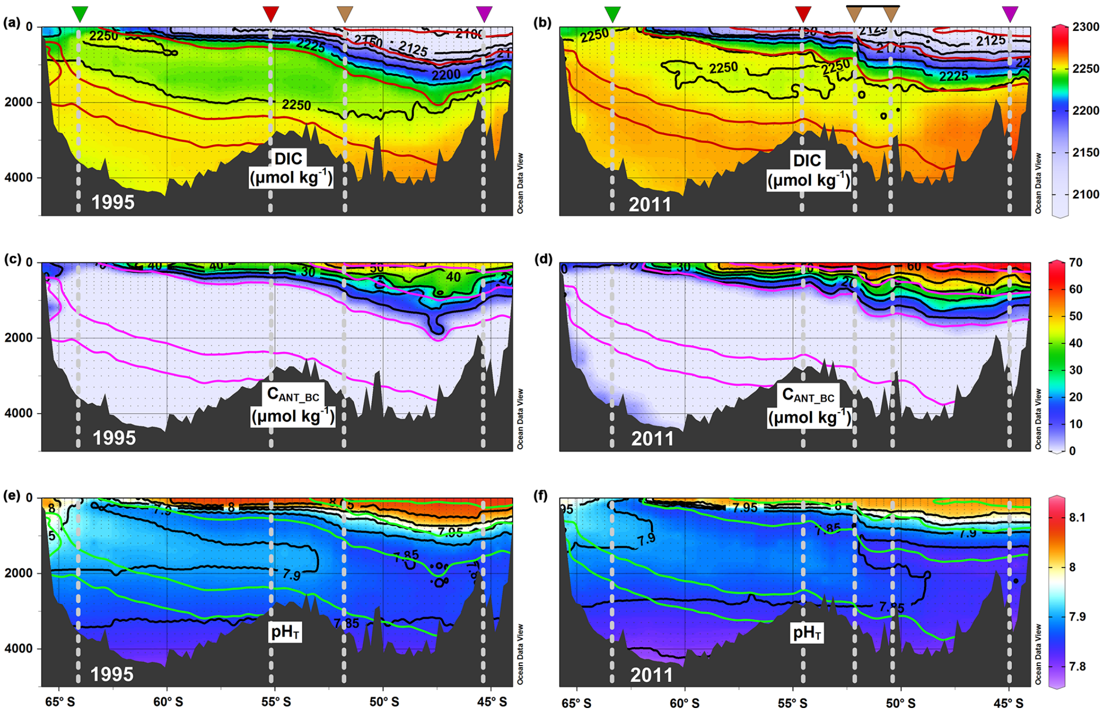



**FIGURE 11:** Changes in the carbon system between Tasmania and Antarctica. The left column shows measurements from 1995. The right column shows measurements from 2011. The top row shows total dissolved inorganic carbon, the middle row shows anthropogenic carbon inventory, and the bottom row shows pH. Note the increased inventory anthropogenic carbon, and lower pH (ie more acidic conditions) in the upper ocean on the northern side of the Southern Ocean (right side of figure panels). (Conde Pardo et al., 2017).

ACE CRC scientists have used the unique time series collected south of Tasmania to document in detail how the ocean inventory of anthropogenic carbon dioxide has evolved over time (Figure 11, Conde-Pardo et al., 2017). The changes in inventory were shown to be the result of a spin-up of the upper limb of the overturning circulation, which is carrying anthropogenic carbon into the ocean interior more rapidly in the most recent measurements.

A decade ago, ocean models and atmospheric observations suggested that the Southern Ocean carbon sink was “saturated” and no longer keeping pace with increases in atmospheric carbon dioxide (Le Queré et al., 2007). The reduction in the Southern Ocean carbon sink was attributed to release of carbon from stronger wind-driven upwelling of carbon-rich deep water. This raised concerns about a possible positive feedback to climate change, if the Southern Ocean carbon sink continued to weaken in the future.

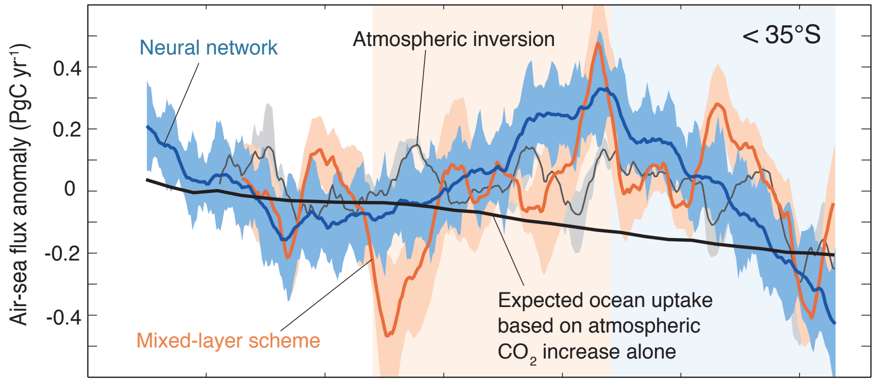



**FIGURE 12:** Evolution of the Southern Ocean carbon sink anomaly south of 35°S. The lines show the integrated air-sea $CO_2$ flux derived from two complementary surface ocean $pCO_2$ interpolation methods. These estimates are compared with the expected uptake based on the growth of atmospheric $CO_2$ alone, based on simulations with the Community Climate System Model (CCSM3) (18). All data are plotted as anomalies by subtracting the 1980–1990 mean flux from each method.

However, new observations of ocean carbon from ACE CRC scientists and colleagues have revealed unanticipated variability in the Southern Ocean carbon sink (Figure 12, Landschützer et al., 2015). These measurements confirm a weakening of the sink in the 1990s, consistent with the earlier work, but show a strong "reinvigoration" of the Southern Ocean carbon sink in the 2000s. The strengthening of the sink was attributed to both changes in wind-driven overturning and changes in the temperature of surface waters, which affect the solubility of carbon dioxide. The magnitude of the variations in strength of the Southern Ocean carbon sink was unexpected and underscores the importance of the Southern Ocean to global carbon budgets (Le Quéré et al., 2017). Understanding the causes of changing Southern Ocean carbon budgets requires sustained and coupled observations of circulation and biogeochemistry. For example, results from the ACE CRC led Southern Ocean Time Series facility of the Integrated Marine Observing System have shown that the Subantarctic Zone takes up a large amount of $CO_2$, despite low biomass, because the growing season is long (Shadwick et al., 2015). $CO_2$ uptake is also enhanced by episodic passage of subtropical waters, which are penetrating southward more frequently in recent years (Conde-Pardo et al., in review).

Expectations for changes in Southern Ocean biogeochemistry include changes in iron supply, the limiting micro-nutrient for primary productivity and thus also biological carbon uptake. Iron measurement capabilities at the required part per trillion levels have only recently become widespread, and thus

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records of change are not yet available. But many of the processes occurring in the Southern Ocean are expected to affect iron supplies, generally favouring their increase. These processes include increasing southward penetration of boundary currents and increasing wind strengths that deliver continental and deep ocean iron, and the release of iron from melting glaciers, ice-shelves, and sea ice (Boyd and Ellwood, 2010). Recent work from the ACE CRC has begun to quantify and model these processes (Bowie et al., 2009; Lannuzel et al. 2011; Tagliabue et al., 2012, 2014; Herraiz-Borreguero et al., 2016; Van der Merwe et al., 2015). The expectation of increases in iron supply has led to the suggestion that the “Greening of Antarctica” that appears to be occurring in response to climate warming on land (Amesbury et al., 2017) may extend to increased productivity in the Southern Ocean (Moore et al., 2018). Increased biological productivity may, in turn, influence the ocean uptake of carbon dioxide.

# THE FUTURE OF ANTARCTICA AND THE SOUTHERN OCEAN

The Southern Ocean influences climate, sea level and biological productivity on global scales, so continued change in the region will have widespread consequences.

Several approaches can be used to assess future change and its impacts, each of which has strengths and weaknesses. Physical understanding provides useful constraints on likely trajectories of the coupled system, but does not deliver quantitative projections. Comprehensive earth system models provide the most quantitative information, but suffer from persistent biases in high southern latitudes and some important processes are not represented. The impact of changes in natural and human systems can also be assessed by considering alternative scenarios that follow from choices made today, providing a holistic but somewhat speculative perspective on the future. Here we briefly consider the future of the Southern Ocean through these three lenses.

Recent advances in understanding of the circulation of the Southern Ocean and its sensitivity to change, as outlined in Section 3, provide insight into what we might expect in the decades and centuries ahead (Rintoul, 2018a). Many of the changes observed so far are consistent with a stronger overturning circulation, driven by stronger winds over the Southern Ocean. The westerly winds shifted south and strengthened between the 1980s and early 2000s, in response to the ozone hole, greenhouse gas increases and changes in the tropics. In response, the overturning circulation increased, carrying more heat and carbon dioxide into the ocean interior.

The westerly winds are projected to strengthen further in response to increasing greenhouse gas forcing. As the climate warms, we can anticipate an increase in heat input to the ocean and an increase in precipitation and ice-melt (both sea ice and ice shelves). The addition of heat and freshwater will convert a larger volume of cold, upwelled deep water to lighter intermediate water, strengthening the upper cell of the overturning circulation. We therefore expect the tendency for delayed warming near Antarctica, and enhanced ocean storage of heat and carbon further north, to continue in the decades and centuries ahead.

The future of the Southern Ocean carbon sink is less certain. More upwelling of carbon-rich deep water means more outgassing and a weaker ocean sink for carbon dioxide; more downwelling of surface waters enriched with anthropogenic carbon dioxide will strengthen the Southern Ocean carbon sink. The net impact on the carbon sink depends on the response of the circulation and eddy field to wind changes, as well as changes in surface temperature (Landschützer et al., 2015). Characterisation of these Southern Ocean variations has also contributed importantly to the assessment of global

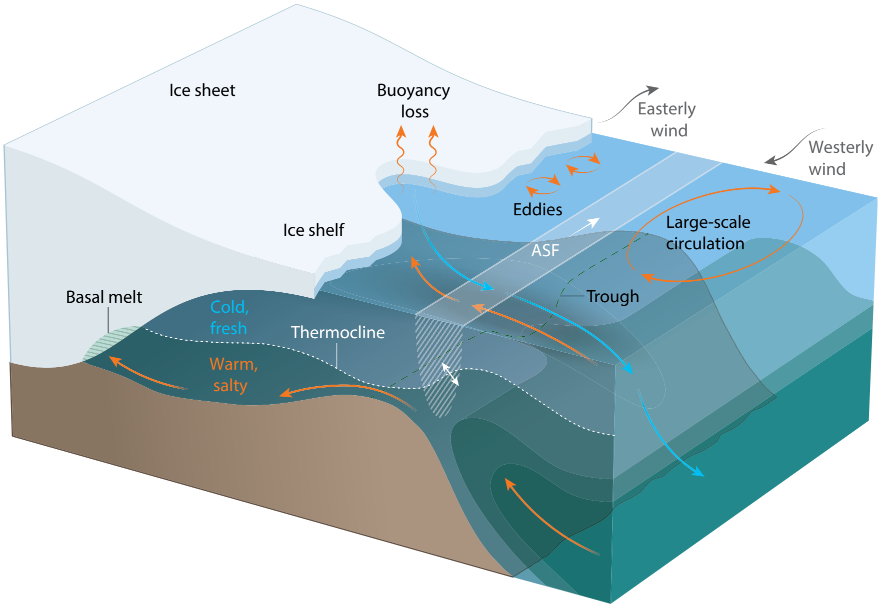


**FIGURE 13:** A schematic view of processes that control ocean heat flux to Antarctic ice shelves. Heat from the open ocean must cross the Antarctic continental slope and continental shelf to reach the ice shelves. This pathway is regulated by a large number of phenomena, including regional and large-scale ocean currents, eddies, sea-floor topography, air-sea interaction, tides and wind forcing. The sensitivity of these processes to changes in forcing are poorly understood.

carbon budgets and their evolving feedbacks to climate (Le Quéré et al., 2017; Matear and Lenton, 2018).

Stronger wind-driven upwelling could also increase the melting of floating ice shelves by the ocean. However, the controls on ocean-driven melt remain poorly understood. As illustrated in Figure 13, many physical processes influence the transport of warm ocean waters from the open ocean to the Antarctic margin. Climate change, and associated changes in wind, sea ice and ocean currents, will influence all of these processes, but in ways that are not yet understood. On the other hand, the recent acceleration in mass loss from Antarctica has been attributed to increased ocean-driven melt of ice shelves (IMBIE, 2018), underscoring the potential importance of future changes. Uncertainty in how ocean-driven melt of ice shelves will change in the future is one of the most urgent gaps to be filled in Antarctic and Southern Ocean science.

Earth system models, as used for example in the IPCC assessments, provide the most comprehensive and quantitative tool for projecting future changes. These models show the westerly winds are likely to strengthen in response to increased greenhouse gas forcing (Bracegirdle et al., 2013). This may drive changes in the overturning circulation and influence the ocean sink of heat and carbon dioxide, as described above. Model projections also indicate the surface layers of the Southern Ocean will warm, with delayed warming near Antarctica and enhanced warming north of the ACC, and freshen as a result of increased precipitation and melt of sea ice and ice shelves (Downes and Hogg, 2013; Armour et al., 2016). However, climate models suffer from a number of persistent biases in the Southern Ocean, including westerly winds that are too far north, poor representation of clouds and radiative forcing, and sea ice trends that do not agree with observations. These biases limit confidence in certain aspects of the model projections.

Earth system models can also be used to assess the response of biogeochemical cycles to climate change. One recent study illustrates the critical role of the Southern Ocean in controlling global nutrient cycles. As noted above, in today's ocean, nutrients exported from the Southern Ocean in intermediate layers ultimately reach the surface to support 75% of global primary production north of 30°S (Sarmiento et al., 2004). What will happen in the future? A recent study suggests that a warming climate will provide better conditions for phytoplankton growth as a result of shifts in ocean currents, warmer temperatures, higher iron availability, and increased light as a consequence of sea ice retreat and higher stratification (Moore et al., 2018). This, in turn, would lead to more sinking of organic matter and trapping of nutrients in the Southern Ocean. As more nutrients are exported downward rather than transported northward, productivity at low latitudes decreases (Figure 14). This has the effect of decreasing global primary productivity by 24% by the year 2300, with an associated 20% decrease in potential fishery yields.

However, just as present earth system models have biases in their representation of the physical system, the biological and biogeochemical components of such models are also subject to significant uncertainties. A mechanistic understanding of the response of phytoplankton to multiple drivers is needed to complement the model-based studies. One example of such work is a recent ACE CRC publication presenting results of incubations of particular phytoplankton species under conditions expected to be typical of the year 2100 (Boyd, 2019). This work shows that the response of Southern Ocean phytoplankton to warming is different in different species, and depends on iron availability. The implication of this work is that the phytoplankton community, and therefore biogeochemical cycles and ecosystems, are likely to shift as the climate changes. Given the connections between Southern Ocean and global nutrient cycles, the implications of these community shifts may be wide-ranging.

A third approach to assessing future change and its impacts is to consider plausible future scenarios, guided by the best-available science. For some variables, this will include quantitative projections from earth system models. For other variables, including many human factors, quantitative information is not available but the past can provide a useful guide to future behaviour. In this way, holistic but necessarily speculative future scenarios can be developed to explore the possible consequences of different pathways. The next section outlines one such exercise for Antarctica and the Southern Ocean in the year 2070.

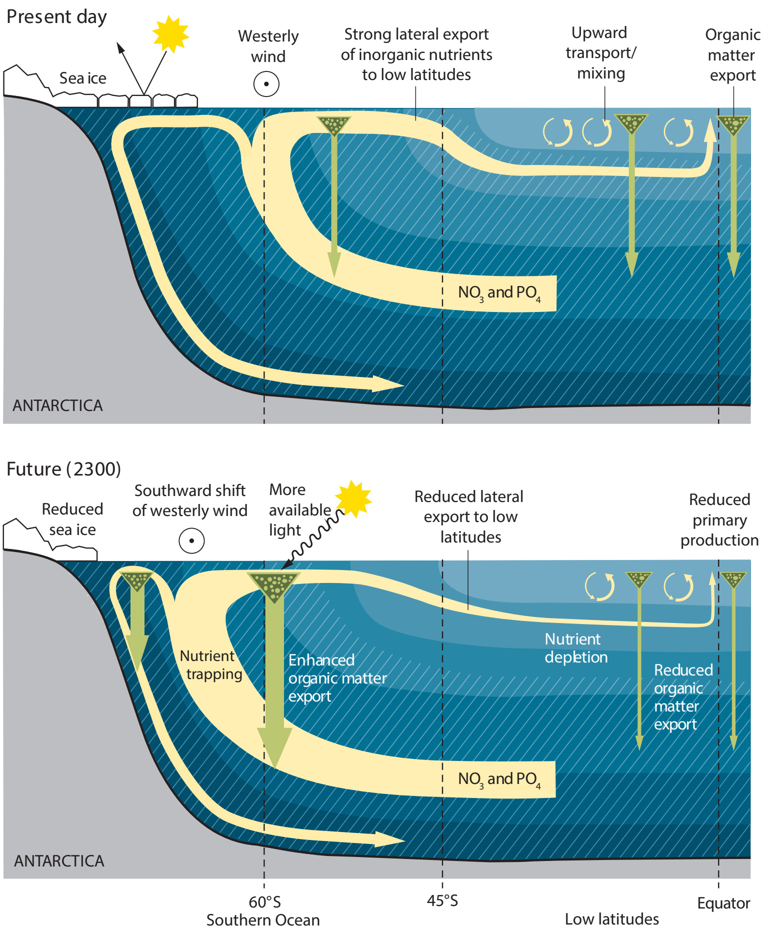


**FIGURE 14:** Ocean circulation and primary productivity in the Southern Ocean. Today, the Southern Ocean plays a key role in the transport of nutrients to lower latitudes. A model study shows that this may change as a result of climate change. Under a high-emission scenario, nutrients will be trapped in the Southern Ocean, reducing nutrient export to low latitudes. This has the effect of decreasing global primary productivity by 24% by the year 2300, with an associated 20% decrease in potential fishery yields. Hatching indicates elevated nutrient concentrations (Laufkötter and Gruber, 2018; perspective on results from Moore et al., 2018).

# ANTARCTICA IN 2070 - THE CHOICE IS OURS

What will Antarctica look like in the year 2070, and how will changes in Antarctica impact the rest of the globe? The answer to these questions depends on choices we make in the next decade, according to a recent study by ACE CRC scientists and colleagues (Rintoul et al., 2018b).

The paper contrasts two potential narratives for Antarctica over the coming half-century – a story that will play out within the lifetimes of today's children and young adults.

While the two scenarios are necessarily speculative, two things are certain. The first is that once significant changes occur in Antarctica, we are committed to centuries of further, irreversible change on global scales. The second is that we don't have much time – the narrative that eventually plays out will depend on choices made in the coming decade.

Matt Curnock

Despite being the most remote region on Earth, changes in Antarctica and the Southern Ocean will have global consequences for the planet and humanity.

For example, the rate of sea-level rise depends on the response of the Antarctic ice sheet to warming of the atmosphere and ocean, while the speed of climate change depends on how much heat and carbon dioxide is taken up by the Southern Ocean. Furthermore, nutrients exported from the Southern Ocean support marine ecosystems throughout the global ocean.

We considered two narratives of the next 50 years for Antarctica, each describing a plausible future based on the latest science.

In the first scenario, global greenhouse gas emissions remain unchecked, the climate continues to warm, and little policy action is taken to respond to environmental factors and human activities that affect the Antarctic.

Under this scenario, Antarctica and the Southern Ocean undergo widespread and rapid change, with global consequences (Figure 15). Warming of the ocean and atmosphere result in dramatic loss of major ice shelves. This causes increased loss of ice from the Antarctic ice sheet and acceleration of sea-level rise to rates not seen since the end of the last glacial period more than 10,000 years ago.

Warming, sea-ice retreat and ocean acidification significantly change marine ecosystems. And unrestricted growth in human use of Antarctica degrades the environment and results in the establishment of invasive species.

In the second scenario, ambitious action is taken to limit greenhouse gas emissions and to establish policies that reduce human pressure on Antarctica's environment.

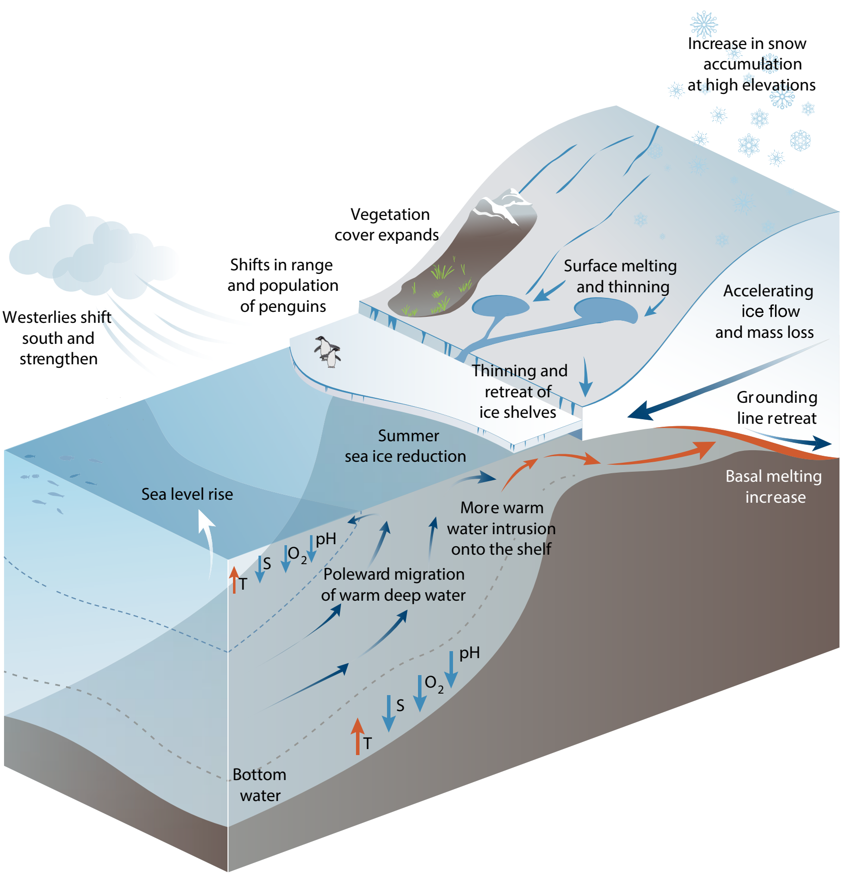


**FIGURE 15:** Under the high-emissions scenario, widespread changes occur by 2070 in Antarctica and the Southern Ocean, with global impacts.

Under this scenario, Antarctica in 2070 looks much like it does today (Figure 16). The ice shelves remain largely intact, reducing loss of ice from the Antarctic ice sheet and therefore limiting sea-level rise.

An increasingly collaborative and effective governance regime helps to alleviate human pressures on Antarctica and the Southern Ocean. Marine ecosystems remain largely intact as warming and acidification are held in check. On land, biological invasions remain rare. Antarctica's unique invertebrates and microbes continue to flourish.

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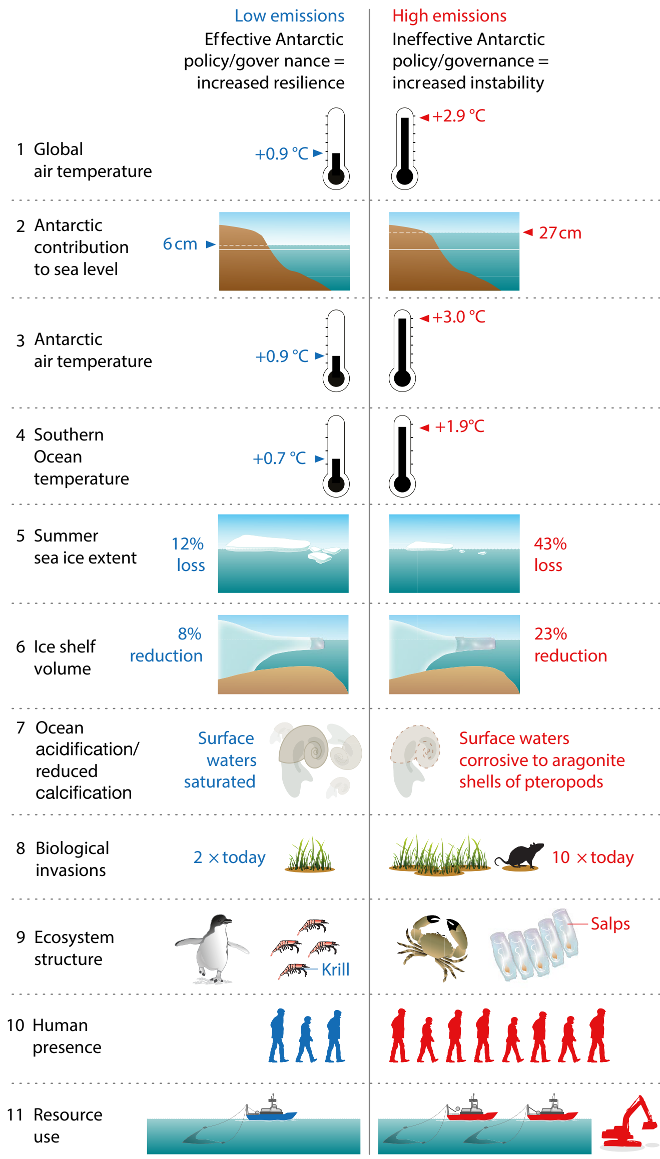


**FIGURE 16:** Antarctica and the Southern Ocean in 2070, under the low-emissions (left) and high-emissions (right) scenarios. Each of these systems will continue to change after 2070, with the magnitude of the change to which we are committed being generally much larger than the change realised by 2070.

Adrian Boyle

Global warming is determined by global greenhouse emissions, which continue to grow. This will commit us to further unavoidable climate impacts, some of which will take decades or centuries to play out. Greenhouse gas emissions must peak and start falling within the coming decade if our second narrative is to stand a chance of coming true.

If our more optimistic scenario for Antarctica plays out, there is a good chance that the continent's buttressing ice shelves will survive and that Antarctica's contribution to sea-level rise will remain below 1 metre.

On the other hand, under continued high emissions, many Antarctic ice shelves will be lost. The Antarctic contribution to sea-level rise will likely exceed 0.4 m by 2100, accelerating to as much as 3m by 2300, and with an irreversible commitment of 5-15m in the coming millennia.Sea-level rise of 1 m or more would displace many millions of people and cause substantial economic hardship.

We can choose which of these trajectories we follow over the coming half-century. But the window of opportunity is closing fast.

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