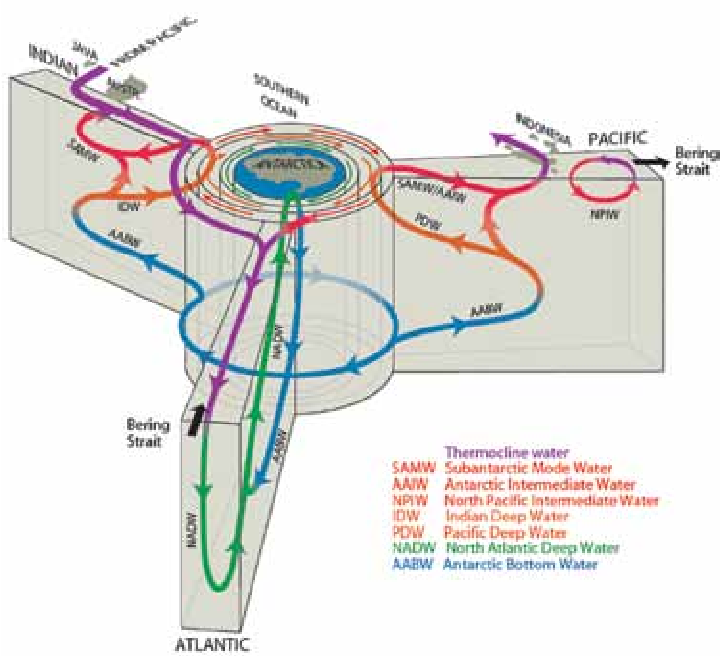
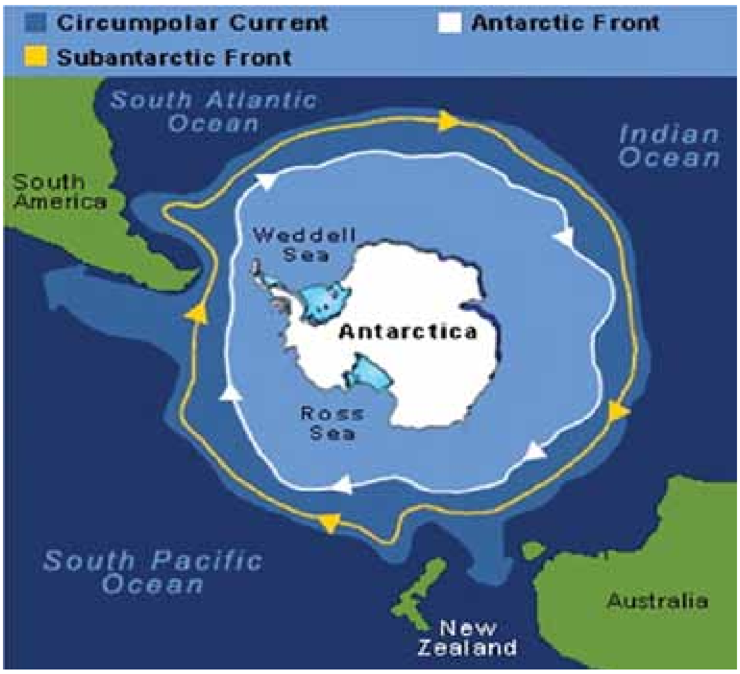
How are **Antarctica** and the **Southern Ocean** responding to **climate change**?



The Southern Ocean connects with the Atlantic, Pacific and Indian Oceans through both horizontal and vertical (overturning) circulation that is part of the deep and very slow moving global 'conveyor belt' circulation. Physical oceanographers recognise different water masses (e.g. Antarctic Bottom Water, AABW) on the basis of characteristic temperature and salinity properties – their 'finger-print', which is unique to each different water mass.
Image: Courtesy of the Southern Ocean Observing System (SOOS) Science Plan, 2013 (www.soos.aq)



Major ocean currents and oceanic fronts (boundaries) around Antarctica. The light blue shaded area is the Antarctic Circumpolar Current (ACC), bounded to the north by the Antarctic Front, also known as the Antarctic Polar Front (APF). The darker blue region is the sub-Antarctic, which lies between the sub-Antarctic and the APF. Image: www.theenergylibrary.com

Antarctica and the Southern Ocean – Earth's 'freezer'.

By **Mike Lucas**, **Kirti Gihwala** and **Michal Viskich**

The continent of Antarctica, covered by its vast 4 km thick freshwater ice-sheet, is the coldest and windiest place on Earth, where winter temperatures can plummet to below -40°C. It's ice sheet continuously flows slowly and inexorably towards the sea, where at the ice shelf, icebergs split off and drift northwards, taking six months or more to melt. Surprisingly perhaps, Antarctica is a cold desert region because it experiences so little rainfall as snow. During winter, 24 hours of darkness envelops the continent for six months until the sun re-appears in spring, once again bathing this white desert in 24 hours of sunlight during summer. Antarctica is completely encircled by the cold and tempestuous Southern Ocean, which averages just 2-4°C in temperature. This unique easterly-flowing ocean has a major influence on global ocean circulation and extends from about 35°S to the Antarctic continent. In the austral winter, frozen 1-2m thick sea ice covers 20 million km^2 of the ocean's surface, but in summer when the sea ice melts, this cover shrinks to just 2 million km^2. In the early years of polar exploration, ships trapped in the sea ice were often crushed and sank – giving rise to epic tales of hardship, courage, leadership and survival, as epitomised by Ernest Shackleton and his crew on his ill-fated ship, *Endurance*. But that is another story for another time!

Both Antarctica and the Southern Ocean are closely coupled to global climate by inter-ocean and ocean-atmosphere linkages, making this region a very important component of Earth's climate system – helping to cool our planet. Drake's Passage, the narrow ocean between South America and the Antarctic Peninsula (56-62°S), allows the Antarctic Circumpolar Current (ACC) to flow continuously eastwards around Antarctica, driven by prevailing westerly winds – the *roaring forties* and *furious fifties*. These winds drove the great three-masted sailing ships of the 18th century eastwards from the Pacific Ocean into the South Atlantic, bound for Europe with their cargos of grain, rice and tea. The ACC is the largest current in the world, dominated south of the Antarctic Polar Front (APF) at about 50°S by water of just 2°C or less. Seawater freezes at about -1.89°C instead of 0°C because of its dissolved salts, which lower the freezing point of water, and when it does so in winter, sea ice is formed.

By connecting with the Atlantic, Pacific and Indian oceans through wind and density-driven overturning circulation – see the diagram – the Southern Ocean has the capacity to store and transport heat, salt and dissolved inorganic carbon (i.e. CO_2 from the atmosphere) throughout these major oceans in a way that significantly influences global climate.

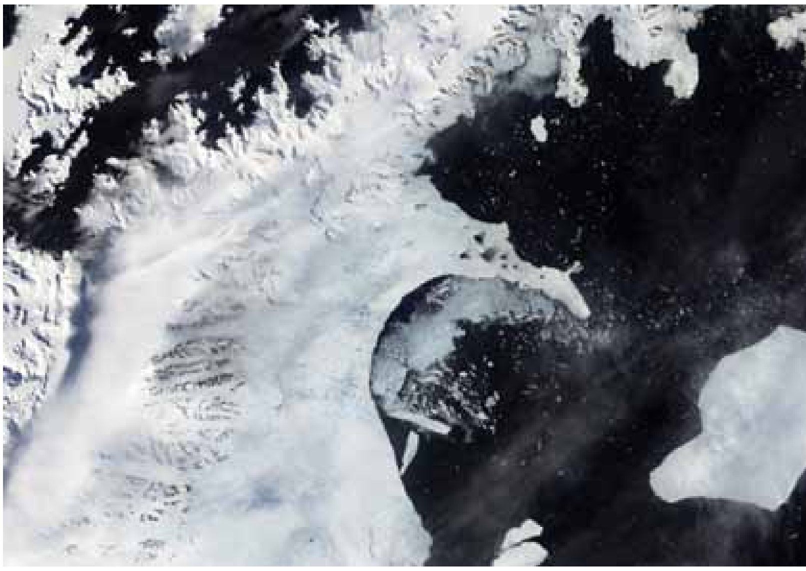
The Southern Ocean captures and stores about 40% of total CO_2 emissions and delivers enough nutrients to other oceans to support 75% of the global ocean productivity north of 30°S. About 70% of the excess heat added to the Earth-atmosphere system by human activities is stored in the Southern Ocean. Global climate and sea level rise are strongly influenced by ocean/sea ice and atmosphere feedbacks. Changes in sea ice extent and continental ice volume alter Earth's albedo (reflectivity), the inter-ocean exchanges of water and nutrients, as well as affecting ocean-atmosphere exchanges of CO_2 and other greenhouse gases. For example, reductions in sea ice extent reflect less heat back into space, creating a positive feedback of further warming. Similarly, models suggest that the Southern Ocean's capacity to take up CO_2 is weakening, so providing another positive feedback of further warming.

Climate change – what is happening?

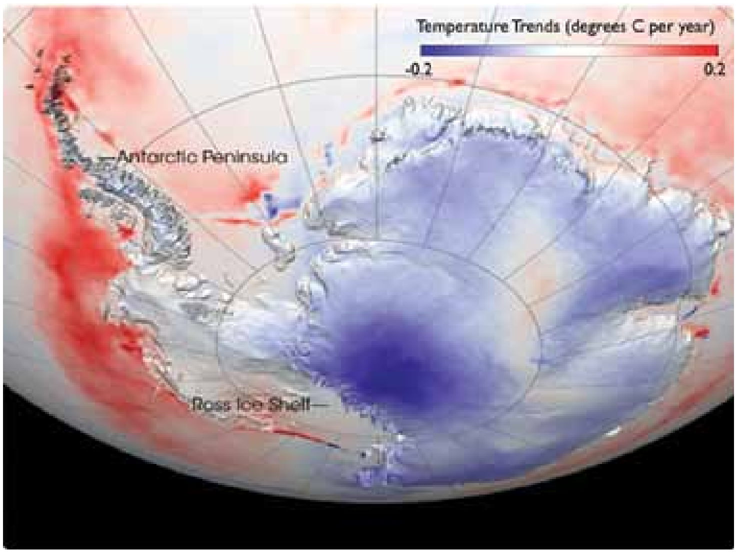
The Scientific Committee of Antarctic Research (SCAR) *Antarctic Climate Change and the Environment Report (2013)*, summarises what climate-driven changes are taking place. Changes in sea ice, ocean warming and rising air temperatures along the western Antarctic Peninsula mean that marine ecosystems here are experiencing the most rapid warming of any marine system on Earth. Marine species here such as penguins and seals are typically well adapted to cope with low temperatures, but poorly adapted to cope with warming temperatures. However, the Antarctic Peninsula has exhibited the fastest regional warming on Earth, of 0.55°C per decade over the past 50 years, relative to a mean global warming 0.11°C per decade over the same period. Winter warming on the west side of the Antarctic Peninsula has been linked to the loss of sea ice on the western side of the Peninsula in the Amundsen-Bellingshausen Sea. On the main part of the continent, West Antarctic warming exceeds 0.1°C per decade in winter and spring, but East Antarctica is cooling. Overall however, the warming trend is positive, and if greenhouse gas concentrations double over the next century, Antarctica could warm by 3°C. Even so, just +2°C warming (in 50-100 years) is considered a threshold where serious ecosystem effects will be felt.

In the Southern Ocean, the ACC flow has strengthened and shifted southwards by 50-70 km since the 1950s.

Antarctic krill, Euphausia superba *(right), form vast swarms of millions of individuals in open water in summer, feeding on phytoplankton, but in winter they feed on ice algae that grow on the underside of the sea-ice (left). Krill are a 'key-stone' species in the Southern Ocean that support almost the entire Southern Ocean food-web.* Image: Wikimedia Commons



The collapse of the 'Larsen B' ice shelf in February 2002, an area the size of Rhode Island in the USA. Image: NASA



Warming and cooling of different regions of Antarctica and the Southern Ocean. Note that the Antarctic Peninsula is warming, while East Antarctica is cooling. Image: Courtesy of the Southern Ocean Observing System (SOOS) Science Plan, 2013 (www.soos.aq)

Gentoo (left) and Adelie (right) penguins.
Images: Wikimedia Commons

Emperor penguins depend on 'fast ice' to breed. The female lays a single egg in the autumn and then promptly passes it to the male before heading off to sea to feed. The male incubates the egg all winter long on his feet, keeping the egg warm in a brood pouch. He and other males in the colony huddle together for warmth, enduring darkness for six months at temperatures of -40°C, and losing 25% of their body weight before they are relieved by the returning females. Tough love! Image: Mike Lucas

A much smaller female elephant seal on Crozet Island shares its beach with King penguins. Image: Mike Lucas

Four-ton elephant seals breed on sub-Antarctic islands, such as Marion Island (above), but feed on fish close to the Antarctic continent. To do so, they can dive as deep as 1 000 m and hold their breath for 45 minutes in pursuit of their prey. Image: Mike Lucas

Increased heat flux into the ocean has warmed near-surface waters by about 1°C since the 1930s (at 0.1°C per decade), but measurable warming extends down to 1 000 m. As a result, the Southern Ocean has captured and stored more heat than any other ocean. The Southern Ocean is also becoming slightly fresher, particularly in the Ross Sea, reflecting glacial ice melt at the continental margins and increased rainfall. As a result, Antarctic Bottom Water formation in the Indian and Pacific sectors has become fresher and less dense, which has the potential to change the deep ocean 'conveyor belt' circulation.

Satellite-derived measurements reveal that ice shelves are thinning along the margins of the East Antarctic Ice Sheet, but especially so along the West Antarctic Ice Sheet. Total ice-shelf loss on both sides of the Antarctic Peninsula over the last 50 years has been about 28 000 km^2, resulting in a global sea level rise of about 0.2 mm per year relative to Greenland ice-sheet melt of 0.39 mm per year. Shelf-ice loss is not due to atmospheric warming, but due to warming from below by warm water inflow that has its origins in the tropical Pacific Ocean, pointing to climate-linked changes in broad global ocean circulation patterns.

From 1979 to 2010, sea ice cover over the Southern Ocean as a whole has increased by 1.3% per decade, reaching a record extent of over 20 million km^2 in 2012. Even so, substantial decreases in sea ice extent around the Antarctic Peninsula have resulted in an 80% decline in regional Antarctic krill density between 1976 and 2004.

This is because krill feed on algae that grow on the underside of the ice in winter, so as sea ice disappears, so does their food. Declining krill populations have negative knock-on impacts on penguin, seal and whale consumers of krill. At Palmer Station, on the western Antarctic Peninsula, ice-dependent Adelie penguin populations are rapidly declining, but are being replaced by sub-polar Gentoo penguins. Emperor penguins in East Antarctica now exhibit low breeding success because of the lack of krill and reduced sea ice extent. Changing ocean circulation, ice cover and the scarcity of fish to eat have also caused a southerly shift in elephant seal populations.

Deeper wind-driven mixing in the higher latitudes of the Southern Ocean has increased ocean-atmosphere

Did you know?

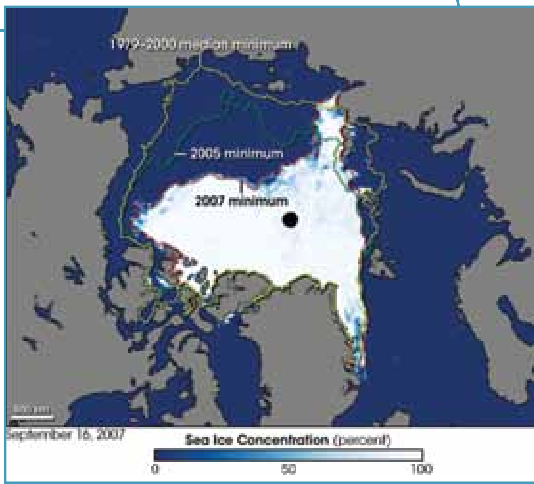
At the South Pole, Antarctica is the most southern of all continents, covering an area of about 14 million km². It is covered by a permanent freshwater ice sheet that is over 4.5 km thick in places, divided into the West Antarctic Ice Sheet and the East Antarctic Ice Sheet, separated by the 3 400 km long Transantarctic Mountains.

The highest peak is the Vinson Massif, rising to 5 140 m. Antarctica's height is three times that of any other continent, averaging 2 300 m of elevation. The weight of ice is so heavy that it depresses the Earth's crust into the shape of a bowl. Because of its position at the 'bottom of the world', Antarctica escaped human discovery for over 2 000 years. It was not discovered until barely 150 years ago, when *Terra Australis Incognita* was sighted for the first time. Scientists worry that the West Antarctic Ice Sheet is becoming unstable in the face of global warming and may melt, as it is doing in some places along the Antarctic Peninsula. By contrast, the East Antarctic Ice Sheet is cooling. Together with the Greenland Ice Sheet in the northern hemisphere, these two ice sheets lock up about 90% of Earth's freshwater in the form of ice.

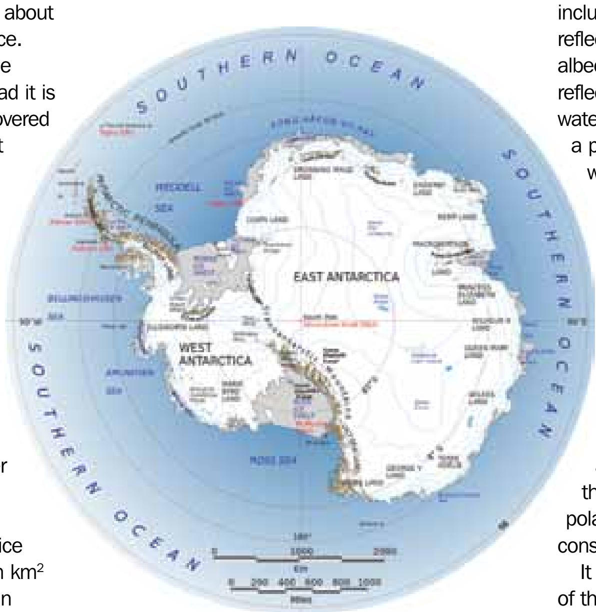
By contrast, the Artic region covering the North Pole is not a land mass at all. Instead it is an ocean – the Arctic Ocean – which is covered by floating sea ice 1-2 m in thickness that seasonally increases in extent during winter, but melts and retreats during summer. However, serious changes are underway. Changing Arctic sea-ice cover is recognised as one of the four major or indices of climate change by the International Geosphere-Biosphere Programme (IGPB), an organisation that monitors and engages in research on global change. The loss of Arctic sea ice due to global warming and melting over the past few decades has been faster than even the most pessimistic of future predictions.

The northern hemisphere summer sea ice minimum has shrunk from nearly 8 million km² in 1980 to just a little over 4 million km² in 2007 – a loss of nearly 50% in just 27 years. Maximum winter sea ice extent has declined by about 1.5% per decade since the 1980s, while multi-year (or permanent) sea ice cover has declined by about 10% per decade over the same period. Ice thickness is also declining and because more open water is appearing, ice drift is increasing, which fragments the area covered by ice. Current rates of sea-ice melt and retreat may have passed a 'tipping point', where recovery in the near future is unlikely and if so, sea ice loss will accelerate. Some models predict that summer sea-ice will vanish by 2085 – perhaps even as soon as 2050.

Why is this happening when Antarctic sea ice extent is mostly stable? There are several reasons for this. Firstly, northern hemisphere temperatures are rising faster and to higher levels than southern hemisphere temperatures. Secondly, the Arctic Ocean is not as isolated or as large as the circumpolar Southern Ocean, which, together with the vast size of Antarctica, exerts a very much stronger cooling influence. Instead, the Arctic Ocean is connected via several ocean currents with the warmer North Atlantic and North Pacific oceans, which results in heat exchange between these ocean basins. In short, the Arctic is more vulnerable to warming, so sea ice there is melting faster.



Arctic sea ice coverage as of 2007 compared to 2005 and compared to 1979–2000 average. Image: NASA



A map of Antarctica. Image: NASA

One consequence of Arctic sea ice loss includes changes in the ability of the Earth to reflect excess heat back into space – called the albedo effect. While snow-covered ice strongly reflects solar radiation, exposed and much darker water has a very low albedo effect. This creates a positive feed-back loop leading to further warming. Sea ice is also a major habitat for a number of important marine mammals, including the ringed seal (*Phoca hispida*), the most numerous seal in the Arctic, as well as the larger bearded seal (*Erignathus barbatus*). Both seals rely on sea ice to reproduce and moult, and neither species is found where sea ice is absent. This is bad news for Polar bears, which feed extensively on these seals. Polar bears themselves use sea ice as a habitat, and as this disappears, it is likely to endanger their populations and survival. Just how polar bears will fare in the future is a matter of considerable concern and debate.

It is hard to imagine that the iconic whiteness of the Arctic may give way to an entirely blue ocean in summer by the end of the century, but that is almost certainly where it is heading.

gaseous exchanges, including that of CO_2. Ocean uptake of CO_2 is causing 'ocean acidification', which is felt most acutely in cold polar oceans, with adverse consequences for some phytoplankton species and important components of the food web, such as pteropods (sea butterflies) and krill. Deeper mixing has also resulted in a 30% decline in phytoplankton production over the last 25 years, which has altered phytoplankton community structure from larger to smaller species. This again has a negative impact on krill and consequently alters the Southern Ocean food-web structure, making it less efficient and more vulnerable to change.

Why are these impacts felt so strongly in the Southern Ocean?

Many of the physical, chemical and biological changes in the Southern Ocean can be linked to the increasing wind strength of the circumpolar westerly winds. But what has caused this? Since about 1980, the ozone hole has had a major impact on the climate of high southern latitudes, increasing westerly wind strengths over the Southern Ocean by 15-20%. This has caused the deeper ocean mixing and also slightly cooled the continental interior, as well as decreasing the growth rate of both terrestrial and marine plants. However, ozone hole recovery is on the way. Ozone-depleting chlorofluorocarbons (CFCs) in the stratosphere are decreasing by about 1% per year, so by the end of the 21st century, ozone concentrations will have almost completely recovered. **Q**

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