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ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

POSITION ANALYSIS: changes to Antarctic sea ice: IMPACTS

Australian Government
Department of the Environment, Water, Heritage and the Arts
Australian Antarctic Division

UTAS

CSIRO

Australian Government
Bureau of Meteorology

CRC AUSTRALIA

Position Analysis: Changes to Antarctic sea ice: impacts.

PA05-090615

ISSN: 1835–7911

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Established and supported under the Australian Government's Cooperative Research Centre Programme.

Photo cover: Australian Antarctic Division.
Page 2 and 3: Sandra Zicus.

executive summary

In Antarctica, the seasonal growth and decay of sea ice is one of the greatest changes on the surface of the Earth, and one that has an extraordinary influence on ocean circulation, global climate and Southern Ocean ecosystems.

Sea ice is frozen seawater and is important because it:

- Plays a significant role in driving global ocean circulation;
- Is a key feature of Southern Ocean marine ecosystems;
- Provides an insulating layer between atmosphere and ocean; and
- Reflects a high percentage of incoming solar radiation.

Two characteristics of sea ice – extent and thickness – are important indicators of the polar response to climate change.

Sea ice extent is a measure of the limit to which sea ice extends from the poles and has been monitored from satellites on a daily basis in both hemispheres since 1979. This satellite data record shows that sea ice in the two polar regions has responded to climate change quite differently over the past three decades. The average annual sea ice extent in the Arctic has declined by 2.9% per decade since 1979 while summer extent has decreased dramatically by 11% per decade (Stroeve *et al.*, 2007). In Antarctica however, the changes have been much more subtle and regionally variable, with a net increase of 1% per decade (Comiso and Nishio, 2008).

The different responses in sea ice extent in the two polar regions appears to be a paradox in the climate change debate; however the changes are largely consistent with known climate processes (Overland, 2008). The small net increase in Antarctica belies the much larger regional differences that are linked to changes in large-scale atmospheric circulation, and in turn to CO_2 increases in the atmosphere and a reduction in stratospheric ozone (Turner *et al.*, 2009).

The western Antarctic Peninsula region has shown a decrease in sea ice extent, consistent with the recent change to more northerly winds and the surface warming observed there, while there have been increases elsewhere including the Weddell and Ross Seas.

While sea ice thickness is known to be sensitive to climate change it remains one of the most difficult of all climate parameters to measure. Currently there is no means to routinely measure and monitor sea ice thickness over large-scales, although satellite radar and laser altimeters show great potential in this respect.

To date, most of our knowledge on the changes in Arctic sea ice thickness comes from de-classified sonar data from military submarines. In the Antarctic, however, no such data are available, and equivalent instruments deployed on deep-ocean moorings are highly susceptible to destruction by drifting icebergs.

Current climate models show large discrepancies and uncertainties in simulating the present-day extent and thickness of sea ice, and in predicting changes in both hemispheres. The observed decrease in the Arctic has occurred more rapidly than predicted by climate models, while the observed net increase and regional variability in the Antarctic was not predicted at all. Still, climate models predict that by 2100 Antarctic sea ice will reduce by 24% in total extent and 34% in total volume, with possible delays in observed reduction until stratospheric ozone recovers (Turner *et al.*, 2009).

While field studies have yielded extremely valuable information on sea ice characteristics, and satellite data have provided a detailed record of ice extent and concentration since the late 1970s, the Antarctic sea ice zone remains one of the most data sparse region on Earth.

1. introduction

Sea ice around Antarctica plays a key role in driving global ocean circulation, structuring ecosystems and providing a habitat for many species of wildlife.

In response to a warming climate, sea ice is forecast to reduce by 24% in extent and 34% in volume by 2100. Coupled with the changes already occurring in the Arctic, this could have far reaching effects on global climate and wildlife. It would also allow greater access to Antarctic waters for both tourist and fishing vessels.

To respond to the challenges of climate change Australian governments need accurate assessments of likely future changes. By improving our understanding of the nature and scale of Antarctic sea ice processes, we can contribute to the development of sea ice models, thereby improving the accuracy of forecasts from regional and global climate models.

The aims of this position analysis are to:

1. Inform Australian governments and the community about the state of Antarctic sea ice research;
2. Outline how sea ice influences, and responds to, global climate variability and change; and
3. Identify issues for consideration in policy development.

Photo: Sandra Zicus.

2. what is sea ice?

Each March, following the Antarctic summer, the surface of the ocean around the Antarctic coast cools to the point of freezing.

Sea ice is frozen seawater and forms at a temperature of approximately -1.8°C. This is lower than the freezing point of fresh water because of the ocean's salinity.

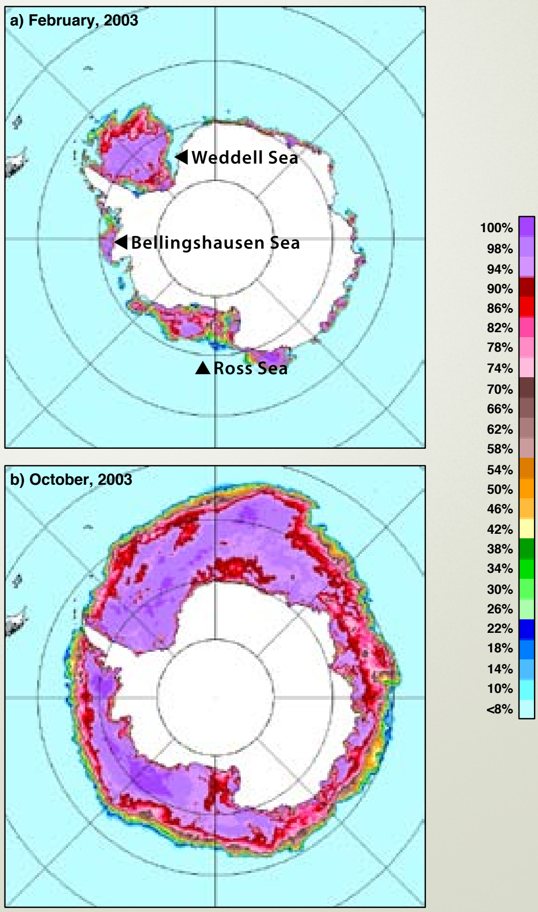
At minimum extent in February, sea ice covers approximately 4 million km^2. However at maximum extent in September/October, the sea ice cover expands to almost 19 million km^2, an area 1.5 times that of the Antarctic continent and nearly three times the size of Australia (Figure 1).

Unlike the continental ice mass covering Antarctica, which has built up over hundreds of thousands to millions of years of accumulated snowfall, most of the sea ice around Antarctica is less than one year old. This is known as 'first-year' ice. First-year ice is regionally variable, but on average grows to approximately 0.5–1.0 m thick. Ice drift and deformation play an important role in determining the thickness of the ice – often ice does not grow to more than 0.1–0.2 m thick before being broken up by the action of wind, waves, ocean currents and tides, and rafted or piled into ridges. The net result is a complicated mixture of different types and thicknesses of ice and open water that is constantly moving and changing. These processes of mechanical redistribution can form pressure ridges that may reach several meters or more in thickness. The volume of ice contained in pressure ridges is one of the unknown features of Antarctic sea ice that current research is working to address.

Sea ice that survives the summer melt season is known as 'second-year' ice, unless it survives more than one summer, in which case it is referred to as 'multi-year' ice. The Weddell Sea, Bellingshausen/Amundsen Seas and eastern Ross Sea are areas in the Antarctic where second-year ice is common. These are not only some of the southernmost regions around the coast, but they are also areas where ice is pushed by winds and ocean currents toward the coast.

Figure 1. ▼
The minimum (Feb) and maximum (Oct) sea ice cover in 2003.

Data from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) launched onboard the NASA Aqua satellite in 2002. The colour scale shows ice concentration, which is the percentage of the ocean surface covered by sea ice. *Source: Dr J. Comiso, NASA/Goddard Space Flight Centre.*



3. is sea ice changing?

Sea ice extent is monitored daily by satellites, with routine observations providing a continuous record of both Arctic and Antarctic sea ice extent since 1979.

These data show how the Arctic and Antarctic have experienced significantly different changes over that time.

The average annual sea ice extent in the Arctic has declined by 2.9% per decade since 1979 while summer extent has decreased dramatically by 11% per decade (Stroeve *et al.*, 2007). In Antarctica however, the changes have been much more subtle and regionally variable.

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4, 2007) concluded that there had been no statistically significant change in Antarctic sea ice extent for the period of reliable satellite records (ie, since 1979).

Since the IPCC AR4, additional data together with an improved technique for interpreting the satellite data indicates a slight increase in maximum Antarctic sea ice extent, as shown in Figure 2 (Comiso and Nishio, 2008).

The net trend is +0.9 ± 0.2% per decade and is statistically significant. However regional changes have been much larger. For example, the western Antarctic Peninsula region has shown a decline in sea ice extent, consistent with the recent change to more northerly winds and surface warming observed there, while there have been increases elsewhere including the Weddell and Ross Seas (Figure 3).

The changes in sea ice extent in both polar regions are linked not only to temperature but also to changes in large-scale atmospheric circulation. These in turn are linked to CO_2 increases in the atmosphere (Fyfe *et al.*, 1999) and the depletion of stratospheric ozone (Turner *et al.*, 2009).

The decline in sea ice extent west of the Antarctic Peninsula is coincident with an increase in average winter air temperature of 5.8 °C over the period 1950-2005 (Stammerjohn *et al.*, 2008).

This is much larger than the global average and has been attributed to anthropogenic climate change (Marshall *et al.*, 2006). In contrast, the increasing sea ice extent in the Western Ross Sea is attributed both to strengthening westerly winds around Antarctica (Stammerjohn *et al.*, 2006) and a shift to more southerly winds in that region, both which are consistent with the observed changes in large-scale atmospheric circulation.

While sea ice thickness is known to be sensitive to climate change it remains one of the most difficult of all climate parameters to measure. Currently there are no means of accurately and routinely measuring and monitoring sea ice thickness over large-scales, although satellite radar and laser altimeters show great potential in this respect. To date, most of our knowledge about the changes in Arctic sea ice thickness comes from de-classified sonar data from military submarines, which show decreases of between 0.5–1.0 m over large areas of the Arctic basin. These upward-looking sonars record the depth of the submarine below the ice which in turn can be used to estimate ice thickness. In the Antarctic however, no such data are available, and equivalent instruments deployed on deep-ocean moorings are highly susceptible to destruction by drifting icebergs.

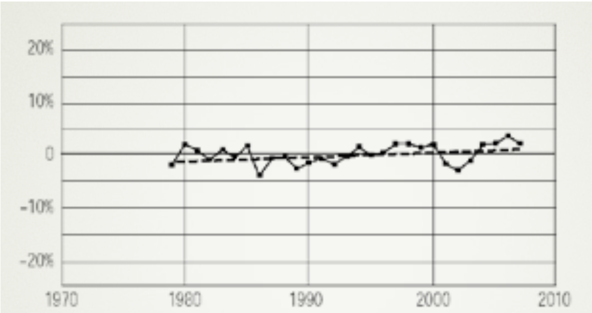


Figure 2. ◀
Antarctic sea ice extent anomaly for September (maximum extent for 1979–2007).

The anomaly is the difference between the maximum extent in any given year and the long-term average. *Source: www.seaice.de*

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3. is sea ice changing?

Australian researchers have developed a technique for estimating sea ice thickness that has resulted in the first circumpolar maps of Antarctic sea ice thickness ever published (Figure 4). These data provide a valuable baseline for climate studies; however monitoring of changes in Antarctic sea ice thickness requires more precise techniques. These are currently being developed by scientists at the ACE CRC and include airborne laser and radar altimetry for surface mapping and sonar measurements using an autonomous underwater vehicle. In addition, ACE CRC research validates satellite-derived information on the thickness of snow cover on sea ice. Data from these programs will be used to improve the interpretation of satellite data and will ultimately contribute to the production of more reliable information about global ice and snow thickness.

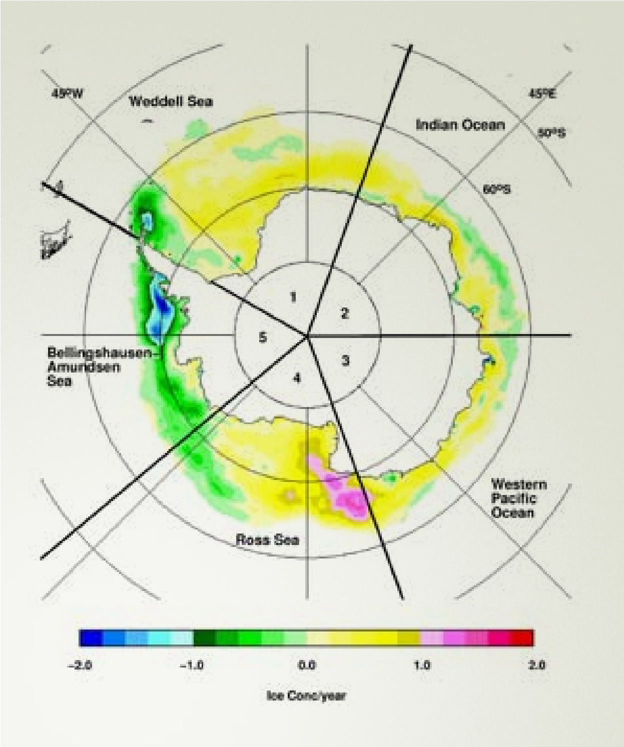


Figure 3. ▲
Regional variability in Autumn sea ice cover around Antarctica for 1979–2007.

Colours show the percentage change in ice concentration per year during autumn. Green/blue shows a net decline in sea ice cover, while yellow/red shows a net increase. *Source: Turner et al., 2009.*

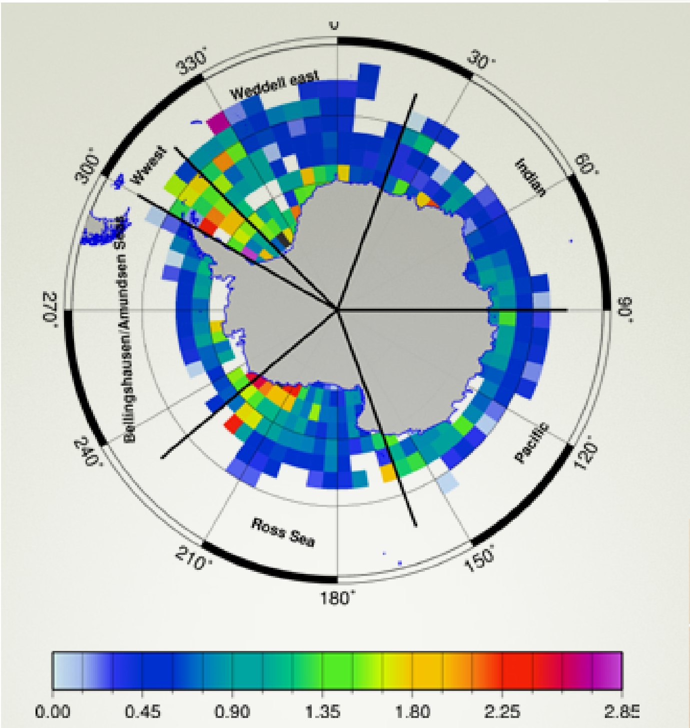


Figure 4. ◀
Circumpolar map of mean annual Antarctic sea ice thickness.

Derived from a compilation of ship-based observations, with values in metres. *Source Worby et al., 2008.*

3. is sea ice changing?

Proxy records of past sea ice extent

Methanesulphonic acid (MSA) is a chemical produced by organisms living in the surface of the ocean, and its production is heavily influenced by the amount of sea ice that forms each year.

Analysis of MSA concentrations from an ice core at Law Dome, near Australia's Casey station, reveals a close correlation between winter ice extent and MSA (Figure 5). Using this MSA-proxy, sea ice extent is believed to have decreased by 1.5 degrees of latitude (equating to a 20% decline) in the Pacific sector of East Antarctica from the 1950s to 1995 (Curran *et al*., 2003). The decline is not uniform however, showing large decadal variations.

Recent studies of MSA records from West Antarctica show a similar sea ice decline in the Weddell, Amundsen, and Bellingshausen Seas (Abram *et al.,* 2008).

A similar result was also reported by de la Mare (1997), who used the noon positions of vessels in the Southern Ocean whaling fleet as a proxy for the sea ice edge in summer. He reported a retreat in Antarctic sea ice extent between the mid 1950s and early 1970s of approximately 2.5 degrees of latitude. A subsequent paper by de la Mare (2008) claims this change is consistent with other sources of historical information including ice charts and direct observations.

Why are Arctic and Antarctic sea ice responding differently to climate change?

The different responses of Arctic and Antarctic sea ice may appear as a paradox in the climate change debate; however they are largely consistent with known climate processes (Overland *et al*., 2008). The differences reflect not only the geographical settings of the northern and southern hemisphere sea ice zones, but also the large-scale atmospheric phenomena that drive surface winds and affect the distribution of sea ice.

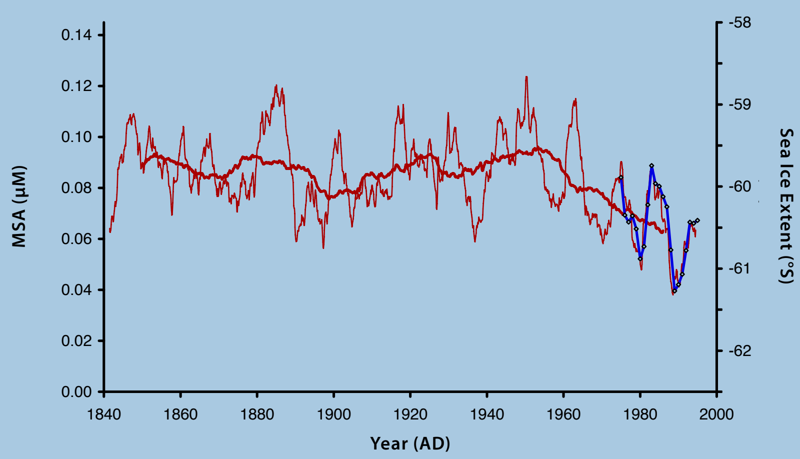
In the Arctic, a combination of steadily increasing surface temperatures, persistent southerly winds in the Pacific sector and warmer ocean currents from the Atlantic, have resulted in thinner sea ice. Much of the older, thicker 'multi-year' ice, which usually survives successive summers, has drifted from the Arctic and melted, leading to a thinner ice cover that is more susceptible to warmer temperatures.

The record summer minimum in Arctic sea ice extent, which occurred in 2007, was not only a result of long-term climate changes but also a set of natural coincidences, including cloudless skies that enhanced incoming solar radiation and strong winds that compacted the sea ice edge (Nghiem *et al*., 2007; Stroeve *et al.,* 2008; Gascard *et al*., 2008).

In the Antarctic, quite different but equally complex processes are at play. There has been a strengthening in atmospheric circulation around the continent which is linked to a reduction in stratospheric ozone (i.e., the ozone hole) as well as to increases in greenhouse gases.

Figure 5. ▼
Law Dome MSA record (1840–1995) and winter sea ice extent 80–140°E sector (1975–1995).

The bold red line shows a 20-year running mean of MSA concentration. The thin red line shows a 3-year running mean concentration of MSA. The blue line shows satellite data for the annual average (Aug-Oct) sea ice maximum in the region 80°–140°E. *Source: Mark Curran et al., 2003.*



3. is sea ice changing?

Over the past several decades atmospheric pressure has dropped over Antarctica and risen in the mid-latitudes of the Southern Hemisphere, causing generally stronger westerly winds around the Southern Ocean (Keeley *et al.*, 2007). This is noticed most in summer and autumn which is 2–3 months later than the observed ozone minimum in the stratosphere. Levebvre *et al.,* (2004) showed that the changes in mean sea level pressure are closely linked to more persistent northerlies over the Antarctic Peninsula, resulting in less sea ice to the west of that region, and stronger southerly winds over the Ross Sea which is causing more expansive sea ice there.

Research is continuing to improve our understanding of large-scale atmospheric circulation around Antarctica and its impact on the distribution of sea ice.

Future impacts of climate change on Antarctic and Arctic sea ice

Current climate models show large discrepancies and uncertainties in simulating the present-day extent and thickness of sea ice, and in predicting changes in both hemispheres. The reduction in Arctic sea ice extent over the past decade, for example, has been much faster than the IPCC models forecast, while the increase in sea ice around Antarctic was unexpected. This serves to highlight the importance of improving the capability of climate models, many of which predict that the Arctic will be ice free in summer by the end of the 21st Century. Based on current observed trends it is possible this could happen much more quickly.

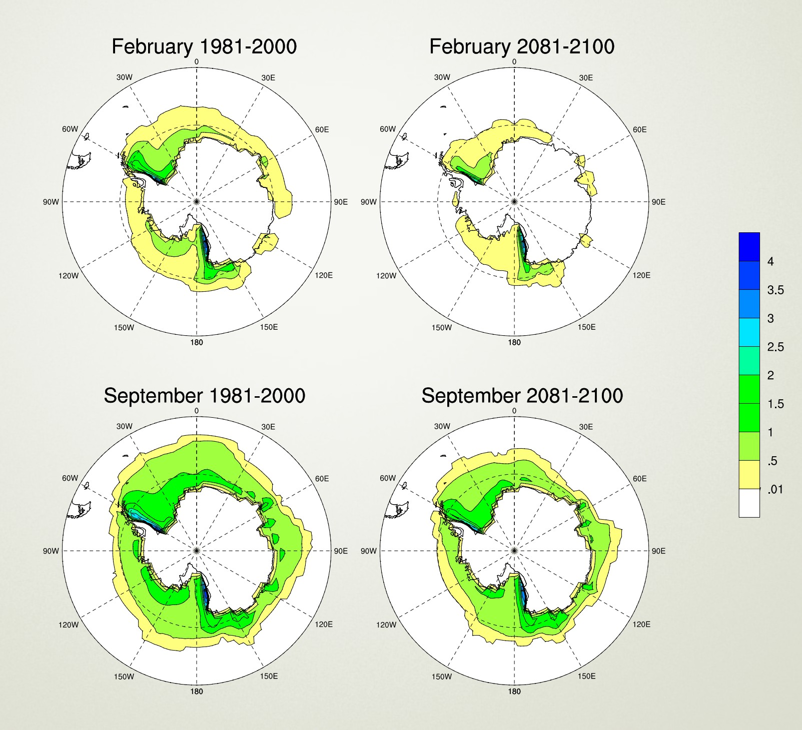


Figure 6. ▲
Predicted changes in Antarctic sea ice extent and concentration.

From the CSIRO coupled model (Mark 3.5) for IPCC scenario A1B (best estimate of temperature rise of 2.8 °C with a likely range of 1.7–4.4 °C). The scale shows sea ice concentration change in percent. *Source: Siobhan O'Farrell, CSIRO.*

While the predicted decline in Antarctic sea ice extent has not been observed to date it is quite possible that changes in thickness may have occurred without detection.

It has been suggested that as future levels of stratospheric ozone recover warmer air will be transported from the mid-latitudes to the polar regions, and surface temperatures over Antarctica are expected to rise (Keeley *et al.*, 2007).

The ensemble average of IPCC climate models shows that, on average, Antarctic sea ice will reduce by 24% in annual mean extent, and 34% in annual mean volume by the end of this century.

In other words we can expect a one-third decline in the amount of sea ice formed around Antarctica each winter (Figure 6).

4. impacts of predicted changes

Sea ice affects the interaction between the ocean and the atmosphere in a number of important and complex ways.

The reflectivity (or albedo) of open water is 7% of the incoming radiation from the sun, compared to more than 80% for thick first year ice with a snow cover. This large difference between the reflectivity of ice and snow surfaces, compared to ocean (or snow-free land) surfaces is the cause of what is known as the 'polar amplification' of climate change. The effect of global warming will be greatest in the polar regions because of the positive feedback between reduced sea ice extent, lower surface reflectivity, and greater absorption of heat by the ocean leading to warmer temperatures and therefore a further reduction in sea ice formation.

As well as reflecting incoming solar energy at its upper surface, sea ice also has an insulating effect on the ocean – an effect which is further enhanced by the addition of a snow cover. Heat in the ocean, which would normally be given up to the atmosphere, therefore remains trapped in the upper layer of the ocean. This is an example of a 'negative feedback', whereby heat trapped in the ocean as a result of sea ice formation may limit or prevent further ice growth. Snow is not only an effective insulator but also greatly limits the amount of sunlight that penetrates through to the ocean. This greatly influences the under-ice habitat and has flow-on effects to other ecosystem processes.

A complicating factor in predicting the impacts of climate change on the sea ice zone is that while the extent and thickness of sea ice may decrease, snow fall in the sea ice zone is expected to increase.

A warmer atmosphere can hold more moisture and therefore produce more precipitation, which may impact on another process known as 'snow ice' formation. When the snow cover on sea ice becomes thick enough to depress the ice below sea level a flooded layer forms and refreezes. Increased snow fall would increase the production of snow ice and while this may counteract any sea ice loss by melting (Wu *et al.*, 2000) it would not compensate for the impacts of reduced sea ice formation on ocean circulation.

The accumulation of snow on sea ice also contributes to the redistribution of fresh water around the Southern Ocean. Snow that accumulates on sea ice will be deposited into the ocean when the ice eventually melts, which could be hundreds to thousands of kilometres away, and many months later.

Sea ice is much less salty than the seawater from which it forms. The salt added to the ocean when sea ice forms makes the surface water more dense, and therefore heavier, causing it to sink toward the bottom. There, it may accumulate in depressions on the continental shelf and eventually mix with warmer, saltier water masses at deeper levels. This is a key process in the formation of Antarctic Bottom Water (Bindoff *et al.*, 2000), and an important link in the global ocean 'conveyor belt' responsible for redistributing heat between the equator and the poles and maintaining our current climate system. The deeper waters brought to the surface as part of the vertical convection beneath the ice are warmer and rich in nutrients, facilitating high biological productivity in the surface waters.

The impacts of changing sea ice cover on Southern Ocean circulation could be significant. Climate models show that the overturning circulation will slow over the coming decades as the Earth warms, sea ice formation decreases, precipitation increases over the ocean and melt-water runs into the ocean from the Antarctic ice sheet. This slowdown will contribute to a further reduction in sea ice extent around Antarctica and result in a decrease in the amount of CO_2 absorbed by the Southern Ocean, both of which represent positive feedbacks and will tend to increase the rate of climate change (Rintoul and Church, 2002).

A loss of sea ice would also change emissions of trace gases from the ocean into the lower part of the atmosphere, including dimethyl sulphide, a gas released by micro-algae that are associated with sea ice (Trevena *et al.*, 2003), and which are a source of cloud condensation nuclei.

4. impacts of predicted changes

Other possible impacts on the atmosphere include changes in circulation patterns, level of cloudiness, and the trajectories of low pressure systems (Menendez *et al*., 1999), which in turn feed back on the distribution and properties of the sea ice. The nature and magnitude of many of these impacts, and the complex feedbacks and connections involved, remain poorly understood but they are the subject of ongoing research.

Sea ice in marine ecosystems

Sea ice affects the structure and function of Antarctic marine ecosystems in complex ways. Changes in sea ice will therefore have multiple impacts on the Southern Ocean, however predicted impacts have high uncertainties.

Antarctic sea ice affects the extent and timing of phytoplankton (i.e., drifting microscopic algae) growth because of its impact on ocean stratification as well as on nutrient and light availability in the surface layer of the ocean. In addition, sea ice harbours algal communities. Model results indicate that up to 28% of the total annual plant production in the ice-covered parts of the Southern Ocean are algae that live within, or are attached to, the bottom of the sea ice (Arrigo and Thomas, 2004). Sea ice also acts as a habitat and a barrier for the larger animals in the region, and plays a critical role in the ecology of Antarctic krill.

Photo: ACE CRC.

4. impacts of predicted changes

▲An overturned ice floe showing the high concentration of algae growing on the underside. Source: Jan Leiser.

Phytoplankton

Sea ice formation starts in autumn when there are substantial concentrations of micro-organisms in Antarctic surface waters. These organisms are incorporated into the newly-forming sea ice by physical processes. Once there, they create ice-associated communities of bacteria and diverse microscopic plant and animal groups.

In terms of biomass, these communities are generally dominated by algae. In fact, the algae can expand to such large numbers that they discolour the sea ice (picture above, top).

Attached to the sea ice and exposed to low but relatively constant light conditions, sea ice algae provide a critical food source for marine herbivores such as Antarctic krill, especially during winter and early spring when food in the water column is scarce (picture above, bottom).

▲Under-ice algae is an important food source for krill. Source: Klaus Meiners

A close relationship between winter sea ice extent and the biomass, condition and reproductive success of krill has been demonstrated in the Antarctic Peninsula region and off East Antarctica (Atkinson *et al.*, 2004, Nicol *et al.*, 2000).

Furthermore, when sea ice melts during spring and summer, low salinity water is released at the surface, which creates conditions favorable to algae growth. The ice melt also releases the ice algae into this stable surface layer of the ocean where they can continue to grow. Some of the released algae sink, thereby contributing to carbon sequestration to the deep ocean.

Recent observations also indicate that iron accumulates in sea ice during autumn and winter and is released in spring (Lannuzel *et al.*, 2007).

Large parts of the ice-covered Southern Ocean are considered as high-nutrient-low-chlorophyll areas, which are characterised by high concentrations of macronutrients (e.g., nitrate, silicate, phosphate) but relatively low concentrations of iron. Therefore iron is the single-most important factor controlling algae growth in these areas and the sea ice cover is a major source of it (Lannuzel *et al.*, 2007).

All of these factors contribute to the formation of major spring-time phytoplankton 'blooms' in the vicinity of retreating sea ice edges. These blooms represent high plant production when compared to open ocean waters of the Southern Ocean, and form biological hotspots by providing concentrated food sources to organisms higher up in the food chain. Scientists estimate that during the month of December these blooms account for 23% of total Southern Ocean plant production south of 50°S, and about 10% annually (Arrigo and Thomas 2004). The resulting enhanced production at the ice edge is exploited by many higher predators, with seals, seabirds and whales congregating there (Ainley *et al.*, 2003).

Changes in sea ice extent, thickness and/or duration will affect both the timing and magnitude of sea ice algae production and phytoplankton production in the Southern Ocean. Models indicate that a decrease in sea ice extent and thickness will result in an increase in overall marine plant production (Arrigo and Thomas, 2004) because greater light availability will increase plant growth in the ice free areas.

4. impacts of predicted changes

A decrease in sea ice extent however, will result in reduced sea ice algal production and probably a reduction in the spring time ice-edge algal blooms, with potentially dramatic flow-on effects to Antarctic marine food webs and ecosystem structures. This may include changes in species distribution and food-web interactions.

Wildlife and Fisheries

Sea ice has multiple effects on the wildlife of the Antarctic region throughout the year. Some species such as Crabeater seals breed on the mobile pack ice while others, such as the Weddell seals and Emperor penguins rely on stable land-fast ice as a breeding platform.

Sea ice also acts as a barrier separating animals from their food source, as well as affecting the food source itself. In spring, Adélie and Emperor penguins must cross many tens of kilometers of coastal land-fast ice from their colonies on the Antarctic continent to reach food supplies for themselves and their newly-hatched offspring (Emmerson and Southwell 2008; Massom *et al.*, 2009).

For krill, the sea ice provides a refuge from predation by air-breathing vertebrates which have difficulty accessing the population during the winter. Baleen whales migrating south from their tropical wintering grounds aggregate along the edge of the pack ice as it retreats in spring, to feast on krill that have spent their winter under the frozen sea (Nicol *et al.*, 2003). Changes in sea ice extent are therefore likely to affect ice-associated baleen whale species such as Minke and Blue whales.

Southern Ocean foods webs are closely attuned to the seasonal rhythms of the Antarctic physical environment, in particular the annual advance and retreat of the sea ice.

Slight alterations to these rhythms have the potential to disrupt the food web. For example, off the Antarctic Peninsula, krill are thought to reproduce successfully in conditions of extensive sea ice extent, and these conditions occur approximately every five years. This is also the average lifespan of an individual krill. Thus, under normal conditions krill can successfully reproduce only once in their lifetime. Should the occurrence of years with above average ice extent shift to a longer periodicity – and there is evidence that it may already have done so in certain regions – large sections of the krill population may never face optimal conditions for reproduction. This could have serious ramifications for the wildlife of the region (Quetin *et al.,* 2007). Krill, and the animals that feed on them, are relatively long-lived and are unable to respond quickly to rapid change.

It is difficult to predict which animals will thrive and which will suffer in a world with less sea ice.

The sensitivity of Antarctic ecosystems to changing sea ice conditions has become increasingly apparent in recent years. In the west Antarctic Peninsula region, the trend towards reduced sea ice has forced ice-loving Adélie penguins to migrate southwards – to be replaced by Gentoo and Chinstrap penguins that previously bred predominantly on northerly sub-Antarctic islands (McClintock *et al.*, 2008).

Photo: ACE CRC.

5. science–policy issues

Photo: ACE CRC.

Climate change projections

Given the connections between Antarctic sea ice and oceanic and atmospheric circulation, as well as marine ecosystems, climate-induced changes to sea ice are likely to have a range of impacts.

Decreases in sea ice extent, thickness and length-of-season will feed back on the rate of climate change, with flow-on effects both globally and in Australia.

To respond to the challenges of climate change Australian governments need precise assessments of likely future changes. By improving our understanding of Antarctic sea ice processes, we can contribute to the development of sea ice models, thereby improving the accuracy of forecasts of regional and global climate change.

In addition to understanding the role of changing sea ice in future climate change, there is a need for a comprehensive, interdisciplinary and integrated approach by policy makers to ensure that the complexities and potential ramifications of changes in sea ice for natural resource management and navigation are fully understood.

Australia has world-class scientific capacity in sea ice research, already integrated with other research programs around the world. This work is increasingly important in relation to planning and completing the IPCC's fifth assessment of global climate change.

To maintain and extend its understanding of climate change impacts, it is in Australia's interest to participate in the working of the IPCC, taking key roles where appropriate. This involvement is only possible through international recognition of Australia's scientific status.

In addition, Australia's research on sea ice ecosystems greatly enhances its engagement with parties to the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), the International Whaling Commission (IWC), the Agreement on the Conservation of Albatrosses and Petrels (ACAP) and the Convention on Biological Diversity (CBD).

Conservation and management

The impact of changes in Antarctic sea ice on the biomass and extent of fish stocks and other marine species is a central issue for conservation and management regimes.

Southern Ocean species may be vulnerable to ecosystem changes. What cannot be predicted at this stage is which species will thrive and which will not, nor how rapid impacts will be. However, there is already evidence of species shifts. In the west Antarctic Peninsula region, for example, changing sea ice conditions have forced Adélie penguins to move southward, and Chinstrap and Gentoo penguins, also moving southward, are replacing them.

Ecosystem changes will have implications for Australia's conservation policies, both domestically and in international forums such as CCAMLR, IWC, ACAP and the CBD. In particular, concern over predicted changes may call for enhanced application of the precautionary approach while further scientific research is being undertaken.

In addition to ecosystem impacts, changing sea ice conditions may heighten fisheries management problems. For Antarctic species, winter is a period of relative relief from fishing pressure, but increased access by both legal and illegal vessels to more southern locations for longer periods may jeopardize this respite.

5. science–policy issues

Any increase in illegal, unreported or unregulated fishing could be devastating to target and non-target species, and undesirable for a number of other reasons as well: CCAMLR's authority could be undermined; fish stocks may not be accurately assessed; quotas could be decreased to reflect increased illegal activity and thus negatively impact on legal fishers; and there could be an increased burden on monitoring and surveillance resources (perhaps even search-and-rescue (SAR) resources). To set appropriate catch quotas, seasons and other conditions, CCAMLR members need to be aware of potential impacts of changing sea ice on fish stocks and broader ecosystem matters.

Navigation

Increased vessel access to more southern locations will have implications for the safety of ocean navigation.

There has been a strengthening of the atmospheric circulation around the continent with stronger westerly winds (Marshall *et al.*, 2006), adding to already hazardous navigation conditions. Localised extreme weather, especially during summer, makes high latitude maritime activities increasingly risky when combined with the presence of seasonal sea ice and icebergs.

The development of an International Maritime Organization (IMO) code for shipping in the Antarctic, comparable to the Arctic Shipping Code, has been delayed (Jensen, 2008) hence there are no restrictions on the kind of vessels that can operate in ice-covered waters. Despite the region being at the limit of (or beyond) an effective SAR capability, all kinds of vessels are now operating in the Southern Ocean.

The presence of these vessels and the difficulty of providing critical SAR response make accurate ice navigation and forecasting technology particularly important. Access to this information increases safety and minimizes time of travel and fuel consumption in ice-covered waters.

Satellite data in the form of ice concentration maps are currently available to navigators, but the maps have a 12–36-hour delay. The software tool, SeaIceView, developed by the ACE CRC, facilitates the use and interpretation of these data.

ACE CRC and Australian Antarctic Division scientists are working to develop short-term (1–5-day) sea ice forecast to help navigators avoid difficult ice conditions.

Tourism

Tourism is the largest commercial activity in the Antarctic and its rate of increase is likely to accelerate with reduced sea ice thickness and extent thereby changing the nature of the summer cruising season. In the 2000/2001 season, 32 vessels conducted 134 voyages, transporting more than 12,000 passengers. By the 2007/2008 season, the figures had risen to 309 voyages with almost 50,000 passengers (IAATO, 2001; IAATO, 2008). Australians are major players in the Antarctic tourism industry (IAATO, 2008).

Cruise ships, rather than icebreakers or ice-strengthened vessels, are an increasing component of Antarctic tourism. Some of these vessels carry large numbers of people; for example in 2008 the *Star Princess*, which has no ice classification, operated two cruises to the Antarctic Peninsula with over 4,000 people onboard each time (IAATO, 2008).

The *Explorer* sank off the South Shetland Islands in November 2007. All 154 passengers and crew abandoned ship following a collision with sea ice. The inquiry into the sinking noted that the Master of the *Explorer* was unfamiliar with the type of sea ice he encountered (*Maritime Reporter*, 2009).

The few rules that do exist are part of the general corpus of international maritime law. In May 2006 the International Maritime Organisation (IMO, to which Australia is a party) adopted Enhanced Contingency Planning Guidance for Passenger Ships Operating in Areas Remote from SAR Facilities (IMO, 2006). This Guidance relies on vessel operators voluntarily complying with strengthened emergency contingency plans. In November 2007 the IMO adopted the *Guidelines on Voyage Planning for Passenger Ships Operating in Remote Areas* (IMO, 2008).

Photo: Tomas Remenyi

5. science–policy issues

Policy initiatives

A key to developing policy options addressing climate change is improved assessments of projected changes. Significant reductions in the extent of Antarctic sea ice by the end of the century and beyond are predicted. Ongoing research on sea ice dynamics, extent and thickness and the climate change feedback mechanisms that exist are important elements of improving these assessments.

Given the role of Antarctic sea ice in atmospheric and oceanic circulation, this work is crucial in understanding regional and global climate change. It is therefore very important that the Australian Government continues to support sea ice research.

Other policy initiatives that may be considered include:

- Raising in CCAMLR the possible consequences of changing sea ice conditions in relation to ecosystem impacts and potential for increased fishing activities;
- Implementing the IMO Voyage Planning Guidelines through domestic legislation; and
- Assisting in the work being undertaken by the Antarctic Treaty Parties and the IMO to develop a detailed Antarctic shipping code for all vessels operating in the Antarctic Treaty area.

6. conclusion

Climate models predict that Antarctic sea ice will reduce by almost a quarter in total extent and over a third in total volume by 2100.

Such reductions will lead to changes in oceanic and atmospheric circulation and will impact the ecosystems of the Southern Ocean including its wildlife. They will also impact on the length of time vessels spend in the Antarctic, with reduced thickness and extent of sea ice allowing greater access for longer periods for both tourist and fishing vessels.

While field studies have yielded extremely valuable information on sea ice characteristics, and satellite data have provided a detailed record of ice extent and concentration since the late 1970s, the Antarctic sea ice zone remains one of the most data sparse region on Earth.

A focused, multi-disciplinary research program is essential for improving our understanding of the complex interactions and feedbacks between the physical and biological systems. In particular, long term research on sea ice thickness is of key importance in monitoring climate related changes in this region.

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References

Science

Abram, N., J. McConnell, E. Thomas, M. Curran and R. Mulvaney, 2008. Developing an ice core reconstruction of regional sea ice changes around Antarctica. Goldschmidt conference, July 13-18, Vancouver Canada, 2008.

Ainley, D.G., C.T. Tynan and I. Stirling, 2003. Sea ice: A critical habitat for polar marine mammals and birds. In: D.N. Thomas and G.S. Dieckmann (eds) *Sea ice - an introduction to its physics, chemistry, biology and geology.* Blackwell Publishing, Oxford. 240–266.

Arrigo, K.R. and D.N.Thomas, 2004. The importance of sea ice for the Southern Ocean ecosystem. *Antarctic Science*, 16, 471–486.

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Arzel, O., T. Fichefet and H. Goosse, 2006. Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modelling*, 12, 401–415.

Atkinson. A., V. Siegel, E. Pakhomov and P. Rothery 2004. Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, 432, 100–103.

Bindoff, N.L, S.R. Rintoul and R. Massom, 2000. Bottom water formation and polynyas in Adélie Land, Antarctica. *Papers and Proceedings of The Royal Society of Tasmania*, 133, 51-56.

Comiso, J.C. and F. Nishio. F., 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *Journal of Geophysical Research*, 113, C02S07, doi:10.1029/2007JC004257.

Curran M., T. Van Ommen, V. Morgan, K. Phillips and A. Palmer, 2003. Ice core evidence for sea ice decline since the 1950s. *Science*, 303, 1203–1206.

de la Mare, W. K., 2008. Changes in Antarctic sea ice extent from direct historical observations and whaling records. *Climate Change*, doi:10.1007/s10584-008-9473-2.

de la Mare, W. K., 1997. Abrupt mid-twentieth century decline in Antarctic sea ice extent from whaling records. *Nature* 389, 57–60.

Emmerson, L. and C. Southwell, 2008. Sea ice cover and its influence on Adélie penguin reproductive performance. *Ecology*, 89, 2096–2101.

Fyfe, J.C., G. J. Boer, and G. M. Flato, 1999. The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophysical Research Letters*, 26, 1601–1604.

Gascard, J-C., *et al*., 2008. Exploring Arctic transpolar drift during dramatic sea ice retreat. *Eos*, 89, 21–22.

Gloersen, P., W.J. Campbell, D.J. Cavalieri, J.C. Comiso, C.L. Parkinson and H.J. Zwally, 1992. *Arctic and Antarctic sea ice, 1978-1987: Satellite passive-microwave observations and analysis* NASA SP-511, National Aeronautics and Space Administration, Washington, DC.

Harangozo, S. A., 2006, Atmospheric circulation impacts on winter maximum sea ice extent in the west Antarctic Peninsula region (1979–2001). *Geophysical Research Letters*, 33 L02502, doi:10.1029/2005GL024978.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor, and H.L. Miller (eds). Cambridge University Press, Cambridge.

Jenouvrier, S., H. Caswell, C. Barbraud, M. Holland, J. Stroeve, 2009. Demographic models and IPCC climate projections predict the decline of an Emperor penguin population, *Proceeding of the National Academy of Sciences*, www.pnas.org/cfi/doi/10.1073/pnas.0806638106.

Keeley, S.P.E., N.P. Gillet, D.W.J. Thompson, S. Solomon and P.M. Forster, 2007. Is Antarctic climate most sensitive to ozone depletion in the middle or lower stratosphere? *Geophysical Research Letters*, 34 L22812, doi:10.1029/2007GL031238.

Lannuzel, D., V. Schoemann, J. De Jong, J-L. Tison and L. Chou, 2007. Distribution and biogeochemical behaviour in East Antarctic sea ice. *Marine Chemistry*, 106, 18–32.

Lefebvre, W., H. Goosse, R. Timmermann and T. Fichefet, 2004. Influence of the Southern Annular Mode on the sea ice-ocean system. *Journal Geophysical Research*, 109, doi:10.1029/2004JC002403, 2004.

Marshall, G.J., A. Orr, N.P.M. van Lipzig, and J.C. King, 2006, The impact of a changing Southern hemisphere annular mode on Antarctic Peninsula summer temperature. *Journal of Climate*, 19, 5388–5404.

Massom, R.A., S.E. Stammerjohn, R.C. Smith, M.J. Pook, R.A. Iannuzzi, N. Adams, D.G. Martinson, M. Vernet, W.R. Fraser, L.B. Quetin, R.M. Ross, Y. Massom and H.R. Krouse, 2006. Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/2, and its profound impact on sea ice and biota. *Journal of Climate*, 19, 3544–3571.

Massom, R.A., S.E. Stammerjohn, W. Lefebvre, S.A. Harangozo, N. Adams, T.A. Scambos, M.J. Pook and C. Fowler, 2008b. West Antarctic Peninsula sea ice in 2005: Extreme ice compaction and ice edge retreat due to strong anomaly with respect to climate. *Journal of Geophysical Research (Oceans)*, 113, C02S20, doi:10.1029/2007JC004239.

Massom, R.A., K. Hill, C. Barbraud, N. Adams, A. Ancel, L. Emmerson and M.J. Pook, 2009. Fast ice distribution in Adélie Land, East Antarctica: Interannual variability and implications for emperor penguins (*Aptenodytes forsteri*). *Marine Ecology Progress Series*, 374, 243–257.

McClintock. J., H. Ducklow and W. Fraser, 2008. Ecological responses to climate change on the Antarctic Peninsula. *American Scientist*, 9, 302–310.

Menendez, C.G., V. Serafini and H. Le Treut, 1999. The effect of sea ice on the transient atmospheric eddies of the Southern Hemisphere. *Climate Dynamics*, 15(9) 659–671.

Nghiem, S.V., I.G. Rigor, D.K. Perovich, P. Celemente-Colon, J.W. Weatherly and G. Neumann, 2007. Rapid reduction of Arctic perennial sea ice. *Geophysical Research Letters*, 34, L19504, doi:10.1029/2007GL031138.

Nicol, S., T. Pauly, N.L. Bindoff, S. Wright, D., Thiele, G.W. Hosie, P.G. Strutton and E. Woehler, 2000. Ocean circulation off east Antarctica affects ecosystem structure and sea-ice extent. *Nature*, 406, 504–507.

Nicol, S., A.P. Worby, and R. Leaper, 2008. Changes in the Antarctic ecosystem: potential effects on krill and baleen whales. *Marine and Freshwater Research*, 59, 361–382.

Overland, J., J. Turner, J. Francix, N. Gillett, G. Marshall and M. Tjernstrom, 2008. The Arctic and Antarctic: two faces of climate change. *Eos*, 89(19), 77–178.

Parkinson, C. L, 2004. Southern Ocean sea ice and its wider linkages: Insights revealed from models and observations. *Antarctic Science*, 16, 387–400.

Quentin, L.B., R.M. Ross, C.H. Fritsen and M. Vernet, 2007. Ecological responses of Antarctic krill to environmental variability: can we predict the future? *Antarctic Science*, 19(2) 253–266.

Raphael M.N., 2003. Impact of observed sea-ice concentration on the Southern Hemisphere extratropical atmospheric circulation in summer. *Journal of Geophysical Research*, 108, D22: 4687, doi:10.1029/2002JD003308.

Rintoul, S., and J. Church, 2002. The Southern Ocean's global reach: a crucial cog in Earth's heat engine. *Australian Antarctic Magazine*, 4, 2–4.

Serreze, M.C., M.M. Holland and J. Stroeve, 2007. Perspectives on the Arctic's shrinking sea ice cover. *Science*, 315, 1533–1536.

Stammerjohn, S.E., D.G. Martinson, R.C. Smith, X. Yuan and D. Rind, 2008. Trends in Antarctic annual sea ice retreat and advance and their relation to ENSO and Southern Annular Mode Variability. *Journal of Geophysical Research*, 113, C03S90, doi: 10.1029/2007JC004269.

Stephens, B.B. and R.F. Keeling, 2000. The influence of Antarctic sea ice on glacial-interglacial CO_2 variations. *Nature*, 404, 171–174.

Stroeve, J., M. Serreze, S. Drobot, S. Gearhead, M. Holland, J. Maslanik, W. Meier and T. Scambos, 2008. Arctic sea ice extent plummets in 2007. *Eos*, 89(2), 13–14.

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007. Arctic sea ice decline: Faster than forecast. Geophysical Research Letters, 34, L09501, doi:10.1029/2007GL029703.

Thomas, D. and G. S. Dieckmann, 2003 (eds). *Sea Ice - an introduction to its physics, biology, chemistry, and geology*, Blackwell Science, Oxford.

Thompson, D.W.J., and S. Solomon, 2002. Interpretation of recent Southern Hemisphere climate change. *Science*, 296, 895–899.

Trevena, A.J., G.B. Jones, S.W. Wright, and R.L. Van Den Enden, 2003. Profiles of dimethylsulphonioproprionate (DMSP), algal pigments, nutrients, and salinity in the fast ice of Prydz Bay, Antarctica. *Journal of Geophysical Research*, 108, C5: 3145. doi: 10.1029/2002JC001369.

Turner, J. J.C Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Merideth, Z. Wang and A. Orr, 2009. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, 2009. *Geolphysical Research Letters*, DOI: 10.1029/2009GL037524.

Worby, A.P., C. Geiger, M.J. Paget, M. van Woert, S.F. Ackley and T. DeLiberty, 2008. Thickness distribution of Antarctic sea ice. *Journal of Geophysical Research*, 113: C05S92, doi:10.1029/2007JC004254.

Wu, X., W.F. Budd, V.I. Lytle, and R.A. Massom, 1999. The effect of snow on Antarctic sea ice simulations in a coupled atmosphere-sea ice model. *Climate Dynamics*, 15, 127–143.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, D. J. Cavalieri and P. Gloersen, 2002. Variability of Antarctic sea ice 1979–1998. *Journal of Geophysical Research*, 107, C5: 3041, doi:10.1029/2000JC000733.

Policy

COMNAP, 2007. Council of Managers of National Antarctic Programs, Information Paper 50 International Coordination of Hydrography in Antarctica: Significance to Safety of Antarctic Ship Operations, to ATCM XXX, at www.ats.aq (accessed 20.08.07).

IAATO, 2001. International Association of Antarctica Tour Operators Document 2000 - 2001 Summary of Sea-borne and Land-based Antarctic Tourism. www.iaato.org/tourism_stats.html (accessed 27.01.09).

IAATO, 2008. International Association of Antarctica Tour Operators Document 2007 –2008 Tourism Summary. www.iaato.org/tourism_stats.html (accessed 27.01.09).

IMO, 2002. *International Maritime Organization Arctic Shipping Code, Guidelines for Ships Operating in Arctic Ice-covered Waters*, MSC/Circ.1056–MEPC/Circ.399, 23 December 2002.

IMO, 2006. *International Maritime Organization Enhanced Contingency Planning Guidance for Passenger Ships Operating in Areas Remote from SAR Facilities*, MSC.1/Circ.1184, 31 May 2006.

IMO, 2008. *International Maritime Organization Guidelines on Voyage Planning for Passenger Ships Operating in Remote Areas*, A25/Res.999, 2 January 2008.

Jabour, J., 2007. Underneath the Radar: Emergency search and rescue insurance for East Antarctic tourism. *Tourism in Marine Environments*, 4, 2: 203.

Jensen, O., 2008. Arctic shipping guidelines: towards a legal regime for navigation safety and environmental protection? *Polar Record*, 44(229), 107.

Maritime Reporter, 2009. April. Digital edition http://marinelink.com/en–US/News/article/330307.aspx (accessed 07.05.09).

NASA, 2009. About MODIS, modis.gsfc.nasa.gov/about (accessed 07.01.09).