POSITION ANALYSIS Antarctic Sealce and Climate Change 2014



ANTARCTIC CLIMATE & ECOSYSTEMS CRC

Climate Science for Australia's Future

POSITION ANALYSIS: Antarctic Sea Ice And Climate Change 2014

PA07-131115

ISBN 978-0-646-91260-8

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Coverimage: Le stations set up from RV Aurona Australis during the second Sea Le Physics & Ecosystems eXperiment (SIPEX 2), East Antarctica, spring, 2012. Photo by Jan L Lieser

The ACE CRC is a unique collaboration between core partners the Australian Antarctic Division, CSIRO, the University of Tasmania, the Australian Government's Department of Industry, the Alfred Wegener Institute for Polar and Marine Research (Germany), and the National Institute of Water and Atmospheric Research Itd (New Zealand) and a consortium of supporting partners. It is funded by the Australian Government's Cooperative Research Centres Program.







Australian Government
Department of the Environment
Australian Antarctic Division





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ACECRC ANTARCTIC SEA ICEAND CLIMATE CHANGE POSITION ANALYSIS

PO SIIIO N ANALYSIS:

Antarctic Sea Ice and Climate Change 2014

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This position analysis aims to:

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

Citation: Lieser JL, Massom RA, Fraser AD, Haward MG, Heil P, Lannuzel D, Meiners KM, Melboume-Thomas J, Press AJ & Williams GD (2013), Position analysis: Antarctic sea ice and climate change 2014, Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Tasmania, Australia

G LO SSARY OF TERMS AND AC RO NYMS USED

AADC – Australian Antarctic Data Centre;

Advection - Predominantly horizontal movement of a mass of fluid;

Albedo – The ratio of the reflected solar radiation to the incident solar radiation, usually referring either to the entire spectrum (broadband albedo) or just to the visible part of the spectrum; Altimetry - Measurement of altitude using remote sensing technique, for example a radar or laser instrument;

Antarctic Bottom Water - Cold dense water that is formed near the Antarctic coast, flows down the continental slope to the abyssal plains and drives global ocean currents;

Antarc tic Divergence - Atmospheric/oceanic boundary between the eastward-flowing Antarctic Circumpolar Current and the westward-flowing Antarctic Coastal Current; Areal extent – The size of the area covered (\rightarrow sea ic e extent);

ASAR – Advanced Synthetic Aperture Radar, an instrument on board the European ENVISAT sate lite;

ATS – Antarc tic Treaty System;

AUV – Autonomous Underwater Vehicle, an independent robot used for marine research; AWI – Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany; CCAMIR – Commission for the Conservation of Antarctic Marine Living Resources, part of the Antarctic Theaty System;

Convection - Heat transfer by mass motion of a fluid;

Coupled climate model – Numeric al models of components of the climate system coupled together;

CPOM, UCL – Centre for Polar Observation and Modelling at University College London, United Kingdom;

CRYOS, EPFL – Laboratory of Cryospheric Sciences at École Polythechnique Fédérale de Lausanne, Switzerland;

C SIRO - Commonwealth Scientific and Industrial Research Organisation, Australia; **Dense Shelf Water** – Dense water mass formed on the continental shelf from significant brinerejection during enhanced sea ice formation, such as in \rightarrow polynyas;

Dimethylsulfoniopropionate (DMSP) - Metabolite found in marine phytoplankton, seaweeds, and some species of a quatic vascular plants;

Ekman transport - Wind-driven transport of surface seawater, to the left of the wind direction in the Southern Hemisphere;

El-Niño/Southern Oscillation (ENSO) – A cycle of coherent and sometimes very strong yearto-year variations in sea-surface temperatures, convective rainfall, surface airpressure and atmospheric circulation that occur across the equatorial Pacific Ocean (source: NOAA);

 $\label{eq:Fastice-Sea} \begin{array}{l} \textbf{Fastice} - \textbf{Sea} \text{ ice that has become "fastened" to the shore or between grounded ice bergs;} \\ \textbf{Feedback} - \textbf{When a process triggers a change that in return influences the initial one;} \end{array}$

Fim - Granular, partially consolidated snow that has commenced the transition to ice;

Freeboard – A measure of height of an ice (or snow) surface above a reference level, typically the sea level;

Hydrostatic equilibrium – A fluid is in hydrostatic equilibrium (or balance) when it is at rest, which means that external forces such as gravity and pressure are balanced;

Ice draft - Measurement of the sea ice thickness below the waterline;

Ice rafting – Horizontal pressure process where by one piece of sea ice overrides another; Ice ridging – Sea ice floes collide and pile up along a line, causing a steep-sloped ridge to rise up above the adjacent stretches of level ice, together with a much larger keel below sea level; Ice shelf - A thick and extensive body of glacial ice attached to a coast and floating on the sea, that gains mass by flow from the grounded continental ice sheet and by local snowfall;

Inter annual - Time scale of more than one year but usually less than 10 years;

Interseasonal – Time scale between seasons;

IPCC AR5 – Intergovemmental Panelon Climate Change Fifth Assessment Report;

LiDAR - Light Detection And Ranging, one of the techniques applied for range measurements in a ltime try;

Meridionalexchange – North-south exchange (along a meridian);

Meridional overtuming circulation – G lobal ocean circulation driven by temperature and salinity gradients (also referred to as \rightarrow the mohaline circulation), which transports low-density waters to higher-latitudes in the upper layer and returns high-density waters equatorward at depth.

Mixed layer – Wind-mixed and brine-forced convection layer between the ocean surface and a depth usually ranging between 25 and 200 metres depending on the season;

NASA - National Aeronautics and Space Administration, United States;

NOAA - National Oceanic and Atmospheric Administration, United States;

Pack ice – Any area of sea ice that is not land fast;

Phenology - Timing of seasonal biological events;

Polynya - An anomalous region of open waterorlow ice concentration within the sea ice zone. Polynyas around the Antarctic coast are maintained where wind orocean currents move ice away and are regions of enhanced ice production;

Ocean forcing – Physical constraints exerted by the ocean on the atmosphere or sea ice; **Outerpack** – Northern part of the sea ice zone around Antarctica, connects to the marginalice zone in the north and the innerpack (closer to the coast) in the south;

ROV – Remotely Operated Vehicle, a dependent robot operated through a tether; **Sea ice concentration** - Proportion of the ocean surface area actually covered by sea ice in a given unit area, such as a satellite pixel. For example, 90% ice concentration signifies that 90% of

the given area is covered with sea ice, with the remaining 10% being open water,

Sea ice extent - Area of the ocean covered by sea ice within the bounds of a specified minimum threshold ice concentration (typically taken to be 15%) in any given sector;

Se a WIFS - Sea-viewing Wide Field-of-view Sensor, the only scientific instrument on GeoEye's Orb View-2 (a lso known as Se a Star) sate lite;

Snow ice – \mathbf{k} e layer at the interface between sea ice and the snow on top formed from snow and entrained seawater;

SIPEX 2 – The second Sea Ice Physics and Ecosystem eXperiment, an international multidisciplinary research voyage, into the Antarctic sea ice zone in 2012 (the first SIPEX was in 2007);

Souther Annular Mode (SAM) - Pattern of climate variability between 40 $^{\circ}$ S and 65 $^{\circ}$ S; Synthetic Aperture Radar (SAR) - A form of radar whose defining characteristic is its use of relative motion, between an antenna and its target region, to provide distinctive long-term coherent-signal variations, which are exploited to obtain finer spatial resolution than is possible with conventional beam-scanning means (source: Wikipedia);

The rm o ha line c irc ula tion \rightarrow merid io nalover turning c irc ula tion;

TLS - Te me strial La se r Sc anne r;

WHOI-Woods Hole Oceanographic Institute, MA, United States.

EXEC UTIVE SUMMARY

The annual expansion and contraction of sea ice in the Antarctic represents one of the biggest natural changes on Earth. At its maximum annual extent in September/October sea ice coverextends about 19 million square kilometres of the ocean around Antarctica – one and half times the size of the continent itself. In the summer sea ice shrinks to around 3 million square kilometres.

Antarctic sea ice plays a major role in the global climate system and in the ecology of the Southern Ocean. The sea ice region is the source of Antarctic Bottom Water, a major driver of global ocean overturning circulation. Sea ice is important in reflecting solar energy back into space. It is a habitat and a source of primary production for Southern Ocean ecosystems.

Sea ice cover in the Antarctic is changing. In the west Antarctic Peninsula region, sea ice extent has dramatically reduced, and the length of the sea ice 'season' has also shortened. In the Ross Sea region of the Antarctic, however, the maximum annual extent of sea ice cover has increased and its season extended. Overall, the maximum annual extent of Antarctic sea ice has increased by around 1.5% perdecade since 1979 (or by around 285,000 square kilometres). This compares to a loss of 1.8 million square kilometres of sea ice maximum annual extent in the Arctic.

One important aspect of Antarctic sea ice that we know very little about is change to its volume. While satellites can measure the aerial extent of sea ice, reliable methods to remotely measure sea-ice thickness are only just emerging. In contrast, data from submarines in the Arctic have allowed detailed monitoring of regional changes to Arctic sea-ice thickness over a number of decades.

What is happening in the physical, chemical and biological systems beneath Antarctic sea ice is poorly understood. Because of the critical role of sea ice, it is vital that we develop a better understanding of the future trends in sea ice extent and volume, and consequences for Antarctic and Southerm ocean ecosystems.

Australia is well placed to take a lead role in the se studies - especially in the East Antarctic. Australia has a mature Antarctic research program that has demonstrated that it can collaborate with other nations, and across scientific disciplines, to do the complex science that is required to understand these important issues. Having the logistic and infrastructure capabilities will be vital to ensuring that this important region of the planet is understood.

WHAT IS SEA IC E

Sea ice is frozen seawater that forms when the surface of the ocean cools to the point of freezing (at a pproximately -1.8 °C). Every winter, extensive freezing of the Southern Ocean forms a vast sea ice cover that surrounds the Antarctic continent - to drastically modify the properties of the ocean surface and the interaction between two key elements of the global climate system, namely the ocean and a troosphere. As its density is less than that of seawater, sea ice floats on the ocean surface, where it forms a heterogeneous matrix consisting mainly of ice and small pockets (cells) of brine [*Petric h and Ecken*, 2010], and its characteristics are modified by physical, chemical and biological processes.



Figure 1. Maximum and minimum extent of Antarc tic sea ice (30-year average for 1981-2010).

Are al extent and seasonality

At its maximum annual extent in September/October and as depicted in Figure 1, this sea ice coverextends over an extra ordinary ~19 million square kilometres of the Southerm Ocean [*Cavalie ri and Parkinson*, 2008; *Comiso*, 2010]; by comparison, the area of the Antarc tic continent is ~14 million square kilometres, while that of Australia is ~7.7 million square kilometres. During summer, this areal extent shrinks to ~3 million square kilometres (in February). As described below, this sea sonal expansion and contraction is of immense climatic, biological and biogeochemical importance, and it follows that any significant changes in sea ice areal extent and seasonality (and other characteristics) have wide-ranging and indeed global ramifications. Whereas areal extent is a measure of the area of the ocean surface covered by sea ice at any given time, seasonality collectively describes the timings of annual sea ice advance and retreat and the resultant duration of sea ice coverage for a particular location.

The width of the sea ice zone at maximum extent varies substantially around the continent – from up to ~2200 km in the Weddell Sea sector (where it occupies a deep poleward embayment) to only a few hundred kilometres in some places, notably between 120° E and 135° E. In this region, the coast extends further north than in other regions (with the exception of the roughly north-south trending Antarc tic Peninsula).

How does sea ice form?

The first stage in sea ice development is the formation of individual crystals comprising fine spicules or platelets known as *frazil* ice. With further freezing, frazil crystals coagulate into a soupy layer on the ocean surface known as *grease* ice. Subsequent development depends on whether calm or stormy conditions prevail. Under calm conditions, frazil and grease ice tend to consolidate into thin flexible sheets called *nilas*, which thicken over time. Under stormier conditions, a wide spread process of sea ice development around Antarctica is the *pancake cycle*. By this process and under the influence of wind and wave action, frazil crystals coagulate to form small "pancakes" – or small floes with uptumed edges - on the ocean surface (a floe is defined as a contiguous piece of ice on the water surface). These pancakes subsequently bond toge the rand raft (override by colliding with each other), to eventually form larger floes or a consolidated ice cover. Ice growth also occurs on the underside of existing sea ice as heat is conducted upwards from the ice-ocean interface and through the ice, that is by *the modynamic* growth. This type of ice is called congelation or columnarice.

In general, the accumulation of snow on sea ice older than a few days plays a key role in determining the properties and development of the underlying ice, due to its strong insulating characteristics and high albedo [Sturm and Massom, 2010]. This in turn modifies the overall climatic, biological and biogeochemical function of the ice.

Importantly, snow also makes a significant contribution to Antarctic sea ice formation via the formation of snow ice [*Maksym and Markus*, 2008]. This wide spread phenomenon largely occurs when the weight of the snow is sufficient to depress the ice surface below sea level. The resultant influx of seawater saturates the lower snow layer, which may

UNDERSTANDING HOW SEA IC ETHIC KNESS IS MEASURED



The sea surface is indicated by the thick black line as a reference surface. Sea ice (grey) floats at the surface of the ocean with a snow cover on top (white). Black arrows show the ice thickness, blue arrows snow thickness; the combination of both is referred to as total thickness. The ice freeboard is indicated by the red line and typically sits above the sea surface (at the interface between the sea ice and the snow), but with sufficient snow load can be suppressed below the sea surface, which then leads to snow ice formation (light grey). The sum of snow thickness and ice freeboard is called total freeboard. Ice draft is measured below the surface (green arrows). Different remote sensing techniques can 'see' different surfaces. LiDAR reflects from the snow surface (or ice surface in case of no snow cover) and therefore gives an estimate of snow freeboard. The RADAR penetrates the snow cover and gives an estimate of snow thickness. Electromagnetic Induction (EMI) systems give an estimate of total thickness in combination with LiDAR. Space-bome remote sensing techniques (LiDAR or RADAR) provide measurements of ice or snow freeboard, from which ice thickness can be computed if ice, snow and water density and snow thickness are known.

subsequently freeze to form a type of salty and granular sea ice that accretes to the surface of the existing ice [Je ffries e t a l, 2001].

How old is the sea ice?

In contrast to the continental ice mass covering Antarctica, which has built up over hundreds of thousands of years of accumulated snowfall, most of the sea ice around Antarctica is seasonal and therefore less than one year old - so-called *first-year ice*. This type of ice has a thickness range of 0.3-2.0 m (typically), although greater thicknesses can occurby ice deformation.

Perennial sea ice (ice that survives one ormore summermelt seasons) is generally thicker but is largely confined to the Weddell, Amundsen and eastern Ross seas (Figure 1). These are not only some of the southermost regions around the continent, but they are also are as where ice is pushed by winds and ocean currents toward the coast [Comiso and Nishio, 2008].

Ice motion and deformation

Rather than forming a static, unbroken veneeron the ocean surface, most of the sea ice around Antarctica comprises a highly-mobile aggregation of floes that constantly move with the wind and currents. This is termed packice. Due to the highly-dynamic response of the packice zone to the passage of storms, its characteristic salso change constantly. New areas of open water between floes (termed leads) freeze rapidly under winter conditions to form areas of new ice, whereas existing ice thickens not only thermodynamic ally (via heat loss to the atmosphere) but also dynamically as floes are pushed together and deform under convergent conditions. Moreover, the characteristics of the outer part of the pack, called the marginalice zone, are strongly affected by ocean waves that not only generate new pancake ice formation but also break up existing floes.

Across the greater Antarctic pack, sea ice growth by the modynamic processes alone is self-limiting as the ice thickens to insulate the ocean surface from the cold atmosphere. Ice motion and deformation then play a dominant role in thickening the ice beyond ~0.5 m - ice seldom attains a thickness of >0.1-0.2 m before being rafted or piled into pressure ridges by the action of wind, waves, ocean currents and tides [Allison et al., 1993; Worby et al., 1998]. Such is the power of these mechanical deformation processes that pressure ridges can be up to ten or more metres thick in regions of first-year ice [Massom et al., 2006; Williams et al., 2013].

On horizontal scales of tens of metres to tens of kilometres, the net result of this complex interplay of the modynamic (freeze/melt) and dynamic (deformation) processes is a complicated mixture of different types, ages and thicknesses of ice. On the broader scale of hundreds of kilometres, however, regions or zones with similar characteristics become apparent [Massom et al., 1999; Massom and Stammerjohn, 2010].

Sea ice motion is also a key factor in transporting sea ice (and its snow cover) from one region to another, that is from an area of formation to an area of melt, to affect the freshwater budget of the high-latitude Southern Ocean.

As such, ice drift is one of the most important features of the Antarctic sea ice zone. As discussed later, there are indications that regional patterns of ice drift are changing around Antarctica [Holland and Kwok, 2012], with major implications for ice concentration, extent, thickness, age and seasonality. Sea ice concentration is defined as the percentage coverage of sea ice (versus open ocean) within a given ocean area.



Figure 2. Mean sea ice motion in the Southern Ocean averaged over a 10-year period (1992-2001), with ice drift speeds indicated by lengths of vectors and the background colours. This large-scale map of ice motion was derived from analysis of satellite data. From *Kimura* [2004].



As a background against which to discuss recent ice motion change (in Section 4). Figure 2 shows mean sea ice motion Antarc tic over 10-year period (derived а fro m satellite data). Being a long-term average, these ice-drift patterns climatological stronalv reflect wind and ocean surface current patterns. Outstanding features are the circumpolar band of mean eastward ice motion centred on $\sim 60^{\circ}$ S in the Atlantic sector and ~65° S in the Pacific sector, and a narrow westward-flowing coastal current that is predominantly in the Atlantic and Indian sectors. These two regimes, namely the Antarc tic Circumpolar Current to the north and Antarctic Coastal Current to the south, are separated along the Antarctic Divergence [Heil and Allison, 1999], but are connected in certain regions by northward retroflections, for example along $85^{\circ} \mathbb{E}[Rintoulet al., 2008]$. Other key features are major gyre systems in the Weddell and Ross seas and the Prydz Bay region of East Antarctica.

Figure 3. A projection of the East Antarctic coast, showing the mean percentage of time (per year) with fast ice coverage from 2000 to 2008 (derived from sate lite data). A figure of 100% indicates fast ice that persists throughout each year (that is multi-year fast ice, which can attain considerable thickness). From *Fraser et al* [2012].

Fa st ic e

Not all sea ice is constantly moving in response to winds and currents. A relatively narrow (up to ~200 km wide) but generally consolidated band of stationary or landfast sea ice (fast ice) occurs around the coastal margins of the continent (Figure 3), where it is held in place by coastal promontories, embayments and/or grounded icebergs [*Giles et al.*, 2008]. Fastice can form and break out annually [*He il.*, 2006; *Frase ret al.*, 2012], or can attain great ages and thicknesses in regions where the ice is more tightly locked to the coastal margins [*Ma ssom et al.*, 2010].

THE ROLE OF ANTARCTIC SEA ICE IN THE CLIMATE SYSTEM

Why is sea ice important?

Antarctic sea ice forms a relatively thin but seasonally-extensive and highly-dynamic cover on the surface of the high-latitude Southern Ocean that is intimately tied to patterns of atmospheric and oceanic temperature and circulation. As a result, it is one of the most sensitive indicators of climate change and variability on Earth. Crucially, the ice cover is not only affected by a changing and variable environment, it also plays an active though poorly-understood role in modulating such change and variability via its influence on the ocean and atmosphere. Thus the sea ice, ocean and atmosphere form a complex interactive system. On shorter time scales, it is intimately tied to the weather, and responds rapidly to changes in wind direction and strength associated with the passage of synoptic systems. In this way, the ice edge location can vary by tens of kilometres from one day to the next.

The climatic significance of Antarctic sea ice lies in the major modifying effect it has on a tmosphere-ocean interaction processes and the surface radiation budget, with the annualcycle of a real expansion and contraction constituting one of the largest seasonal geophysical changes on the surface of the planet. Primarily, the ice acts as an insulating blanket between the cold atmosphere and relatively warm ocean, and as a physical barrier to the exchange of moisture, gases and momentum between the two. Being white, sea ice also reflects substantially more sunlight back into space than does open ocean, which is dark and there fore absorbs more sunlight and heats up. This high albedo (reflectivity) characteristic of sea ice is important for climate feedback and amplification processes [Perovich et al., 2008]. These effects are strongly modified by the presence of substantial accumulations of snow on the surface of Antarctic sea ice, given the even greater insulating and reflective properties of the snow [Sturm and Massom, 2010]. In general, the degree to which sea ice affects ocean-atmosphere interactions depends on the ice extent, its concentration and its thickness distribution.

Antarctic sea ice also plays a key role in ocean water mass modification and formation. As it forms and grows, the ice expels salt into the underlying ocean as brine, to increase the salinity and density of the water column [*Toggwe ile rand Samue k, 1995*]. Conversely and in spring, sea ice melt releases fresher water, to form a stable low-salinity ocean surface layer.

WHAT HAS THE MERIZ GLACIER CALVING SHOWN US?



Seal ice production in coastal polynyas, which is critical to the formation of Antarctic Bottom Water (AABW), has declined significantly off George V Land in East Antarctica since the calving of the Mertz Glacier Tongue in February 2010. From *Tamura* et al. [2012].

Scientists from the ACE CRC used satellite data to detect regions of thin ice and attribute the associated heat flux to estimate sea ice production (colour shadled above in metres per year). A 14 – 20% decrease (relative to the mean from 2000—2009) was detected in sea ice production off George V Land in the two winters after the glacier tongue's calving and the associated realignment of vast iceberg B9B [Tamura et al., 2012]. These findings suggest that 50% of this decrease in sea ice production can be attributed to the changes in the icescape post-calving (thick red line) impacting the distribution and strength of polynya activity. The Mertz Glacier Polynya is important to global climate as a site of significant AABW formation [*Rintoul*, 1998].

AnotherACECRC study, by *Shadwick et al.* [2013], has highlighted strong links between this abrupt natural event and biological productivity and carbon drawdown in the region. Specifically, breakout and melt of thick multi-year fast ice released by the movement of iceberg B9B and the Mertz Glacier Tongue led to significant input of meltwater into the ocean surface layers. This likely enhanced the availability of light and iron, supporting a diatom bloom that doubled carbon uptake relative to precalving conditions. Particularly high rates of ocean-atmosphere heat loss and resultant ice formation and brine rejection occur in recurrent and persistent areas of open water and thin ice at certain locations around the Antarctic coast known as polynyas. Within these regions, sea ice is swept away by strong winds and currents as quickly as it forms. In this way, polynyas act as "ice factories" for the wider sea-ice zone. This enhanced sea-ice formation and corresponding salt rejection forms cold, saline Dense Shelf Water that in discrete locations can be transported northward across the shelf break, with sufficient density to mix down the continental slope and produce Antar tic Bottom Water (AABW). This AABW in tum plays a key role in driving global ocean thermohaline circulation. As such, Antarctic coastal polynyas in the southern Weddelland Ross seas and adjacent to the Mertz Glacier tongue and Cape Darnley in East Antarctica are of global significance in spite of being relatively small (10s to 100s of kilometres across). In this way, the influence of sea ice reaches the ocean abyss as well as the tropics [Rinto ule t al., 2001]. Moreover, High-Salinity Shelf Water associated with sea ice formation controls circulation and melt processes under ice she lves [Galton-Fenzi et al., 2012]. It follows that any lasting change to polynya systems could have far-reaching climatic consequences.

Although fast ice comprises a relatively small fraction of overall sea ice area – it varies seasonally between 5% (in winter) and 35% (in summer) for East Antarctica (Figure 3) [Fase ret al., 2012] - it is important for a number of key reasons. For one thing, it too is a sensitive indicator of climate change and variability around the Antarctic coastal margins [Murphy et al, 1995; He il, 2006]. It can also attain a considerable thickness, of >5 m in places [Massom et al., 2010], and thus represents a significant freshwater store. Moreover, fast ice plays an indirect role in global thermohaline ocean circulation by forming a major component in coastal polynya systems [Tamum et al. 2012], and it may in certain regions around the Antarctic coast act to mechanically stabilise floating glacier tongues and ice shelves [Massom et al., 2010]. Last but not least, its presence can both impede and facilitate logistical access to Antarctic bases.

In addition to its important physical role, sea ice dominates the physical and chemical seasonal dynamics of the high-latitude Southern Ocean and plays a crucial role in marine ecosystems [*Smetacek and Nicol*, 2005; *Thomas and Dieckmann*, 2010]. Around the coast, fast ice forms a crucial breeding platform for Emperorpenguins (*Aptenodytes forsten*) and Weddell seals (*Leptonychotes weddelli*) [*Kooyman and Bums*, 1999], and its breakup and the resultant release of nutrients and freshwater into the watercolumn has been associated with algal blooms [*Shadwicketal*, 2013].

Important changes

In the past few years, an increasing number of head lines have reported dramatic changes occurring in the high latitudes (both north and south) - with Arctic summertime (minimum annual) sea ice extent reaching a record minimum in 2012 since sate lite records began in 1979 [Simmonds and Rudeva, 2012] and ice shelves disintegrating along the Antarctic Peninsula [Cook and Vaughan, 2010]. This indicates that climate change is occurring already, and in a way that was not fore seen only a few years ago.

In response to a warming climate, annual mean Antarctic sea ice extent and volume is forecast to reduce by 24% and 34%, respectively, by 2100 [*Arzelet al.*, 2006], with the most pronounced reduction being at the end of summer. This could have far-reaching effects on global climate and marine ecosystems. It would also allow greater access to Antarctic waters for both commercial and research vessels.

RECENT CHANGES IN ANTARCTIC SEA ICE

Sea ice extent: Antarctic versus Arctic

Since 1979, when reliable sea ice data became available from satellite sensors, the two polar regions have experienced markedly different trends in the overall (circumpolar) extent of sea ice coverage. In the Arc tic, the extraordinary decline in annualsea ice extent - of 3.5-4.1% per decade (95% confidence level) for the period 1979-2012 [IPCC, 2013] - is one of the most dramatic and conspicuous examples of climate change anywhere on Earth [Perovich, 2011]. The rate of sea ice loss in the Arc tic, which is particularly strong in summer, is even more rapid than that predicted by models [Stroeve et al., 2007], and has initiated strong climate feedbacks that have enhanced the warming in the region [Screen and Simmonds, 2010].

By contrast and as depicted in Figure 4a, annual sea ice extent around Antarctica has shown a small increasing trend of 1.2-1.8% per decade (around 95% confidence level) for 1979 to 2012 [IPCC, 2013]. The cause of the contrasting responses of the two polar sea-ice covers is subject to lively debate, but is thought to relate to differences in their geographical settings, respective sea ice growth and decay processes, large-scale climate interactions, and ice-ocean interactions and feedbacks [Turner and Overland, 2009; Maksym et al, 2012].

The slight expansion observed in overall Antarctic sea-ice areal extent in fact masks dramatic regionally-contrasting changes that have occurred in both the extent and seasonality of sea ice coverage [Comiso et al, 2011; Stammerjohn et al, 2012]. For ice extent, these regional differences in trends are shown in Figure 4. Most notably, sea ice extent has increased in the Ross Sea sector by $5.0 \pm 0.6\%$ perdecade (for the period 1979-2008), while major loss has occurred in the Belling shausen/Amund sen seas sector (at a rate of -7.1% $\pm 0.9\%$ perdecade). By comparison, trends in the remaining Antarctic sectors are similar to the overall circumpolar trend.

As such, the observed trend towards increased Antarctic sea ice extent overall is in fact the sum of similar trends in East Antarctica and much larger and opposing trends in West Antarctica. A number of hypotheses have been proposed; all suggest that the response of Antarctic sea ice to climate change (and variability) is far from simple. A recent sate lite-based study, for example, suggests that wind-driven changes in sea ice advection are a dominant driver of trends around much of West Antarctica, whereas wind-driven thermodynamic changes dominate elsewhere [Holland and Kwok, 2012]. Other studies have proposed that changes in atmospheric temperature and wind stress [for example Liu et al., 2004; Turne ret al., 2009; Le fe bure and Goosse, 2008] together with



Figure 4. Thends in monthly ice extent, derived from sate lite data and expressed as a nomalies against the long-term mean (1978-2008), in the (a) entire Southern Ocean, (b) Weddell Sea, (c) Indian Ocean, (d) Western Pacific Ocean, (e) Ross Sea, and (f) Bellingshausen/Amundsen seas. From *Comiso et al.*, 2011. Locations are marked on Figure 1.

changes in precipitation [*Liu and Curry*, 2010], ocean temperature [*Jacobs and Comiso*, 1997; *Mere dith and King*, 2005], and atmosphere and/orocean feedbacks [*Zhang*, 2007; *Stammerjohn et al*, 2012] are responsible. There may also be an important link to the ice sheet. *Bintanja et al* [2013] propose that enhanced input of meltwater from basal melting of Antarctic ice shelves (*Pritc hard et al* [2012]) into the upper ocean leads to the formation of a relatively cool and fresh surface layer that shields the surface ocean from the warmerdeeperwaters. These surface layers can then freeze more easily, which could explain why observed overall Antarctic sea-ice extent trends peak in autumn and early winter.

Underpinning the changes and regional contrasts outlined above are large-scale patterns of atmospheric forcing associated with the Southern Annular Mode (SAM) and to El Niño-Southern Oscillation (ENSO)-related teleconnections across the southern Pacific Ocean [for example Renwick, 2002; Yuan and Li, 2008; Stammerjohn et al., 2008; Tume ret al., 2009; Pezza et al., 2012]. Crucially, the dominant circumpolar we sterly wind belt over the Southern Ocean has strengthened by 15-20% and has migrated polewards by 1-2° of latitude since the late 1970s [Korhonen et al, 2010; Tumer and Marshall, 2011]. This change has been linked to a change in the atmospheric pressure gradient in the So uthe m He misphere: pressure has increased at mid-latitudes but decreased around the Antarctic coast [Thompson et al, 2011]. The SAM, which is a measure of this gradient and is the dominant mode of variability in a tmospheric circulation at high southern latitudes [Simmonds, 2003], has changed to a more positive phase in the austral summer and autumn over the past half century. This change has been linked to ozone depletion [Gille tt et al, 2009; Thompson et al, 2011] and increased greenhouse gas concentrations in the atmosphere [Marshall et al, 2004]. It has been noted elsewhere that change and variability in key large -scale climate modes such SAM and ENSO could also arise through na tura l va ria b ility [Ho lland and Kwok, 2012].

A key factor affecting the dramatic changes in sea ice extent in the West Antarctic sector has been the deepening of the Amundsen Sea Low (ASL), which is a recurrent low atmospheric pressure anomaly in the South Pacific, due to the increased intensity of westerly winds and the geographical configuration of the Antarctic continent [*Tume ret al.*, 2013a]. Resultant stronger and/or more persistent so utherly (colder) winds along the western flank of the ASL have generated more extensive sea ice in the Ross Sea, while northerly (warmer) winds in the Belling shausen Sea have led to less extensive ice there. Proxy information on historical sea ice extent which can be obtained from ice cores from the Antarctic Le Sheet [*Cuman et al.*, 2003] and sources such as whaling data [*de la Mare* 1997, 2008] are crucial in terms of extending the satellite data record back in time (before the 1970s) - to place recent change/variability into longer term context. For example, ice core data from the Antarctic Peninsula suggest that sea ice decline in the Belling shausen Sea since the early 1900s due to a progressive deepening of the Amundsen Sea Low [*Abram et al.*, 2010].

Sea ice seasonality

In addition to sea ice extent, changes in sea-ice seasonality are crucially important for a

number of freasons [*Massom and Stamme rjohn*, 2010; *Maksymetal*, 2012]. Lee-free summer duration controls solar heating and wind-mixing of the upper ocean [*Montes-Hugo et al.*, 2009; *Perovich et al.*, 2008], thus affecting sea-surface temperatures [*Mere dith and King*, 2005] and ocean upwelling [*Martinson*, 2012]. Moreover, the life cycles of high-latitude marine organisms (from micro-organisms to whales) are specifically adapted to sea ice and its seasonal mythms [*Thomas and Die c kmann*, 2010], and serious consequences can arise when the serifythms change (see Section 4).



Figure 5. Trends in the length of Antarctic sea ice-covered the se a son (ice duration) for the period 1979/80-2010/11. The se are derived e xte nt from daily satellite ic e records (1979-present), which have been used to determine, for each sea ice year (February to February) and each satellite pixel location, the day sea ice advanced to that location and the day it retreated from that location. Methods are described in Stammerjohn et al. [2008]. after Parkinson [2002]. The black lines denote the mean minimum and maximum ice extents for the same time period. From Maksym et al. [2012].

Strongly contrasting regional changes have also occurred in timings of annual sea-ice advance and retreat and resultant sea ice duration around Antarctica (Figure 5). In contrast to the Arctic, where most regions show trends towards shorter sea ice duration, patterns of regional-scale change in Antarctic sea ice seasonality are accentuated by two regions in particular [*Simpkins et al.*, 2013; *Stammerjohn et al.*, 2012]. These are the Antarctic Peninsula-Belling shausen Sea (AP-BS) and Western Ross Sea (WRS) regions. Of major concern from both a physical and biological perspective is a substantial shortening of the sea ice season (lengthening of the open water season) in the AP-BS region – of 3.3 months over the period 1979/80 to 2010/11. This extraordinary change results from later advance (by ~2 months) and earlier retreat (by ~1.3 months). In fact, the rate of increase in ice-free conditions in the Belling shausen Sea region (of 3.1 ±1.0 days peryear as depicted in Figure 5) is even greater than that which is occurring in regions of greatest ice loss in the Arctic [*Stammerjohn et al.*, 2012].

In stark contrast, the annual sea ice season in the WRS region has significantly lengthened, by ~2.6 months over the period 1979/80 to 2010/11. Here, earlier sea ice advance (by ~1.4 months) is followed by a later retreat (by ~1.2 months).

By comparison, and as shown in Figure 6, patterns of change in the relatively narrow East Antarctic sea-ice zone are farmore complex, comprising mixed signals on regional to local scales [Massom et al, 2013]. Indeed, pockets of strongly positive and negative trends in ice season duration (of ± 2 -3 days peryear) occur in near juxtaposition in certain regions, for example Prydz Bay. A negative trend in sea ice duration (of -1 to -3 days per annum) occurs in fairly isolated pockets in the outer sea ice zone at $\sim 60^{\circ}$ S to 62° S and $\sim 95^{\circ}$ E to 110° E, and in various near-coastal areas, including an area of particularly strong and persistent change near Davis Station and between the Amery and West Ice Shelves. These areas are largely associated with coastal polynyas that are regionally-important as sites of enhanced sea ice production/melt.





While the interplay between large-scale atmospheric patterns (like SAM and ENSO) to some extent explains sea ice variability in the South Pacific sector of the Southern Ocean, it does not explain regional changes observed else where around Antarctica. Moreover, it fails to account for the potentially important role of ocean forcing and feedbacks. The observed magnitude and timing of seasonal/regional sea ice changes in fact point to involvement of strong positive feedbacks. For example, a strong relationship between spring sea ice retreat and subsequent autumn advance observed in the AP-BS (and WRS) regions is consistent with an earlier (later) spring retreat leading to increased (decreased) so lar heating of the upper ocean, which then results in a later (earlier) sea ice advance in the following autumn [Stammerjohn et al., 2012].

Sea ice thickness and volume

In the Arctic, a combination of submarine sonar and extensive satellite altimeter data has revealed a substantial thinning of the ice cover there that is consistent with the loss of perennial ice from the Arctic Basin [Rothrock et al, 2008; Kwok and Rothrock, 2009]. However, no such data are available for the Antarctic sea ice zone, where our current knowledge of sea-ice thickness is limited to compilations of various in-situ and remote sensing observations [for example Worby et al., 2008] that are characterised by large spatio-temporal gaps and may be biased to wards thinnerice [Maksym et al, 2012], and ice chart and satellite altimeter data that are limited to certain sectors or short time periods [for example Zwally et al, 2008; De Liberty et al, 2011; Yi et al, 2011; Kurtz and Markus, 2012]. As such, important large-scale changes in Antarctic sea-ice thickness and volume may be going unnoticed. Satellite remote sensing, using laser and radar altimeters such as those onboard ICES at and CryoSat 2 to accurately measure surface e le vation re la tive to se a le ve l [Yie t a l, 2011; La xon e t a l, 2013], c le a rly re pre sents the only practical means of bridging this critical gap [Figure 7]. Unfortunately, however, there are considerable challenges to deriving accurate and reliable sea-ice thickness estimates from the se data in the Antar tic compared to the Art tic. The se challenges are assessed la ter in this document.



Figure 7. Estimates (uncalibrated) of Antarctic sea ice freeboard height (surface above se a level) at the end of winter in October 2011. derived from CryoSat 2 radar altimeter data. Converting satellite freeboard measurements to ice thicknesses remains a pressing challenge, requiring accurate independent information on snow thickness and volume and ice density [Zwally et al., 2008]. Data such as these only recently became a va ila b le a nd pre se nt an e xc iting ne w development sa te llite in re mo te sensing, providing the third dimension of se a ice estimates. Figure courtesy Rachel Illing, Katharine Giles, Andy Ridout (all CPOM, UCL) and Nathan Kurtz (NASA).

AN INTEGRATED AIRBORNE IMAGING SYSTEM: BRIDGING THE GAP BEIWEEN HIGHLY DETAILED IN-SITU OBSERVATIONS AND LARGE SCALE SATELLITE REMOTE SENSING.



The Australian Antarctic program deploys an airborne multisensor platform to determine a range of sea ice physical parameters. The instrumented helicopter shown carries a downward-looking scanning LiDAR and thermal infrared temperature sensor (pyrometer) under the cowling in the front, and a downward looking high-resolution, medium format digital camera in the camera bucket below the floor of the helicopter. The LiDAR provides information on combined sea ice and snow cover surface elevation (from which sea ice thickness can be computed); the pyrometer measures the temperature of the surface; and the camera records areal coverage of sea ice and roughness characteristics. A snow thickness radiar is a crucial fourth scientific payload and is being developed. This will enable more precise estimates of the snow cover thickness on sea ice, which is one of the important variables when computing sea ice thickness from surface elevation data.

All of these instruments are being used to calibrate and validate satellite remote sensing data, for example from CryoSat-2 (carrying a radar altimeter), or thermal infrared data from polarorbiting satellites. Such airborne capability is key to linking *in-situ* observations made on a very small local scale (100s of metres) with satellite data on much larger (regional to hemispheric) scales. – to improving geophysical products derived from the latter. While satellites hold the key to the large-scale monitoring of sea ice thickness, *in-situ* monitoring programmes remain crucially important in the fast-ice zone, where the ice thickness is intimately associated with atmospheric and oceanic circulation and temperature. Under the auspices of the internationally coordinated Antarctic Fast-Ice Network (AFIN) [*He il et al.*, 2011a], sustained measurements of fast-ice thickness, freeboard and snow thickness are conducted at six locations off the Antarctic coast.

Measurements are taken about once a week. Several AFN locations indicate increased interannual variability in annual maximum ice thickness over the last 15 years, accompanied by more fast-ice breakout events throughout a year – which reduce the integrated fast-ice volume.

Ice dynamics

In-situ observations of East Antar tic sea-ice drift have shown that atmospheric for ing is the main driver of ice motion [He il et al., 2009, 2011b], with recent intensification of storm activity in certain regions of East Antar tica leading to increased deformation and ridging (and therefore thickening) of the ice cover [He il et al., 2011b].

On the broader circum-Antarctic scale, sate lite-derived ice motion analysis [Ho lland and Kwok, 2012] has revealed regional increases in autumn-winter sea ice speed of up to 30% from 1992 to 2009 - most notably in the sectors 20° W- 20° E and 90° W- 140° E, with decreases of similar magnitude in the westem-central part of the Weddell Gyre, the Bellingshausen Sea and off much of East Antarctica (Figure 8). These large and statistically-significant changes are linked to observed changes in surface wind speed and direction associated with change in large-scale modes of climate variability, such as SAM and ENSO [Ho lland and Kwok, 2012]. Other work carried out within the ACECRC (He il et al., in progress) has revealed high interannual variability in ice motion.



Figure 8. Antarctic autumn-winter (April-October) sea ice motion trend vectors for the period 1992-2010, derived from satellite data and overlain on colour coded 19-year change in meridional ice speed. Figure adapted from *Holland and Kwok* [2012].

SIPEX 2: A MILESIONE IN UNDERSTANDING ANTARC'IIC SEA ICE



The Sea Ice Physics & Ecosystems eXperiment 2 (SIPEX 2) was jointly coordinated by the ACE CRC and the Australian Antarctic Division. This multi-disciplinary study was specifically designed to address major knowledge gaps in Antarctic sea ice zone processes as identified by national and international end-users. It was conducted using RSV Aurora Australis in the region of 100° E to 120° E off East Antarctica from September to November 2012, and brought together over 50 scientists from nine nations. The international team measured the physical, biological and biogeochemical properties of sea ice on small-to-regional scales using classical methods and state-of-the-art technology, including ice coring surveys, remotely-operated and autonomous underwater vehicles, drifting buoys and instrumented helicopters. Data from the voyage being processed by ACE CRC and international researchers will enhance our understanding of the role of sea ice in Antarctic climate and ecosystem processes. These data will also be utilised in the validation of satellite-derived sea ice thickness products and the parameterisation of sea ice processes in climate and ecosystem models.

An example of the collaborative and integrative data collected during SIPEX 2 is shown in the graphic below. At the local scale (over a 100 m × 100 m grid), coincident measurement of the ice draft, freeboard and snow loading can provide crucial three-dimensional information at sub-floe scale. This is now possible through the new methodologies for in-situ fieldwork using autonomous underwater vehicles (AUV) and laser and GPS technologies [Williams et al., 2013]. An AUV from the Woods Hole Oceanographic Institution (WHOI), equipped with a swath multi-beam sonar, obtained high-resolution geolocated 3-D maps of Antarctic sea ice draft. Coincident, high-resolution 3-D measurements of snow and ice surface morphology were obtained using terrestrial laser scanners (TLS) and an automated snow probe. The next steps in this approach are to extend the methodology beyond sub-floe scale - to provide regional sampling using, for example, powerful autonomous underwater and airborne instrument packages. The success of these floe-scale missions could pave the way for a new era of field experiments capable of exploring ocean and sea ice processes on scales up to 10–100 kilometres. This increase in scale is important for the goal of directly linking in-situ data with satellite sensor footprints and coupled climate model grid cells and ecosystem studies.



Sea ice surface elevation and draft and snow surface elevation data as collected at a typical sea ice station during SIPEX 2 (units in metres). TIS and snow probe data courtesy Ted Maksym (WHOI) and Emesto Thujillo (CRYOS, EPFL). From *Williams et al.*, 2013.

Fa st ic e

Recent work conducted at the ACE CRC produced the first high-resolution time series of fast ice maps for the East Antar tic coast (covering the Indian Ocean and Western Pacific Ocean sectors) [*Faser et al.*, 2012]. This study shows that fast-ice coverage displays large inter-annual variability, but no statistically-significant trend, in the Western Pacific Ocean sector. In contrast, the Indian Ocean sector showed relatively smaller variability, but a statistically-significant positive trend in fast ice extent of $4.1 \pm 0.4\%$ per year. However, these calculations are based on a short period only (~9 years, 2000-2008), and a longer time series is required to conclusively identify long-term trends. Extending the fast ice record both temporally and to circum-Antarctic is an ongoing focus of work at the ACECRC.

SEA IC EIN SO UIHERN O C EAN BIO G EO C HEMIC ALC YC LESAND EC O SYSTEMS

Sea ice is a key driver of Southem Ocean biogeochemical cycles and plays an important role in structuring Antarctic marine ecosystems [Thomas and Dieckmann, 2010]. Antarctic sea ice cover affects the Southem Ocean chemical and biological processes in variable and complex ways [Massom and Stammerjohn, 2010; Vancoppenolle et al., 2013]. Changes in sea ice will therefore have multiple impacts on the Southem Ocean by affecting its elemental cycling, productivity and food web structures. While many coupled sea ice physical-chemical-biological processes have been identified, they are not generally well understood or quantified at large scales. The potential future impacts of changing sea ice on Southem Ocean biogeochemistry and ecosystem structure and function are therefore highly uncertain.

Sea ice biogeochemistry

Recent observations show that iron accumulates in sea ice during autumn and winter and is released back into the ocean in spring [Lannuze let al, 2007; van der Merwe et al, 2011]. Iron is an essential nutrient for algalgrowth. The Southern Ocean is a high-nutrientlow-chlorophyll area, which is characterised by high concentrations of macronutrients (for example nitrate and phosphate) but low concentrations of iron. Therefore iron availability is a key factor controlling algalgrowth in the Southern Ocean and sea ice can act as a majoriron store [Lannuze let al, 2007]. Release of iron during ice melt contributes to the development of ice-edge blooms which serve as ecological hotspots providing food for Antarc tic krill (Euphausia superba). The krill are in turn exploited by many higher predators including seals, seabirds and whales, which often congregate at retreating ice edges (for example Nicolet al. [2008]).

Previously, sea ice was believed to be impermeable to gases. Large-scale oceanatmosphere carbon dioxide (CO_2) exchange was thought to occuronly during the open water season. However, recent studies point towards significant CO_2 fluxes through sea ice, modulated by a permeable sea ice cover and dynamic biological and chemical processes within the sea ice [De lille et al., 2007; Nomura et al., 2010; Rysgaard et al., 2007]. Current knowledge suggests that sea ice is permeable to gas fluxes and can act as both a source of CO_2 in winter and a sink in summer and autumn, and thus affects the oceanic uptake of this important greenhouse gas in complex ways. On-going research is aimed at determining the processes responsible for the release and uptake of various climate relevant gases from ice-covered oceans [Vancoppenolle et al., 2013].

Sea ice processes are also considered to make a significant contribution to the sulphur cycle through the high production of dimethylsulfoniopropionate (DMSP) by ice algae. DMSP serves as a precursor of sulphate aerosols, which are cloud condensation nuclei and have a potential cooling effect on the planet by increasing cloud albedo [Malin and Kirst, 1997; Stefels et al., 2007; The vena and Jones, 2006].

Sea ice algae and phytoplankton

Sea ice formation starts in autumn when there are substantial concentrations of microorganisms in Antarctic surface waters. These organisms are incorporated into the newly forming sea ice by physical processes and create diverse, ice-associated microbial communities (*Thomas and Die c kmann*, 2010 and references therein). In terms of biomass, these communities are generally dominated by microalgae. In fact, the algae can grow to such high biomasses that they discolour the sea ice (Figure 9).



Figure 9. An overturned first-year sea ice floe showing the high concentration of algae growing on the underside. Photo by Jan L Lieser (November 2009, East Antarc tica).

Observations and model results indicate that 10-20% of the total annual primary production in the ice-covered parts of the Southern Ocean is derived from algae which live within, or are attached to, the bottom of the sea ice [Arrigo and Thomas, 2004; Legendre et al., 1992]. However, these estimates are subject to considerable uncertainty as field observations, which are necessary to validate newly emerging models, remain sparse and are costly to obtain (see Figure 10) [Meiners et al., 2012].



10. Colour coded dots Figure showing the location of ice cores and the associated ice-algal pigment (ice-algal pigment is measured millig rams c hlo ro p hyll-a as of per metre squared). The spatial coverage across six sectors around Antarctica is quite heterogeneous, demonstrating the need for more comprehensive data collection. From *Me ine rs e t a l.* [2012].

While the contribution of sea ice algae to overall primary productivity in the Southerm Ocean is considered to be relatively low, these algae provide a critical food source for marine herbivores such as Antarctic krill, especially during winter and early spring when food in the watercolumn is scare [Flore set al., 2012]. A krill feeding at the underside of an ice floe is shown in Figure 11.

When sea ice melts during spring and summer, low-salinity and less-dense water is added to the ocean surface, which creates stratified conditions that are favourable to algal growth. The melting ice releases nutrients, including iron as well as ice algae, into the stable surface layer of the ocean where the micro algae can continue to grow. In combination, these processes contribute to the formation of major spring-time phytoplankton "blooms" in the vicinity of retreating sea ice edges.



Figure 11. Krill under sea ice. Photo courtesy Hauke Flores (AWI).



Figure 12. Satellite data composite from January 2009 showing surface ocean colour indicative of algal pigment concentration, which is measured in milligrams of chlorophyll-a per cubic metre. Data are taken from the SeaWiFs satellite project, indicating patchiness in the ice-edge bloom around Antarctica. The sea ice is shown in dark grey. Unfortunately, satellites cannot measure algal biomass in the sea ice zone. Figure courte sy Ben Raymond (AAD). Ice-edge blooms can provide, at times and in distinct regions, a highly productive environment supporting higher trophic levels and biogeochemical cycling [Amigo et al, 1998; Smith and Nelson, 1985]. Figure 12 shows the patchiness of chlorophyll-a in a composite of satellite ocean colour data for January 2009, with some hot spots of high productivity for example in the Amundsen Sea, eastern Ross Sea and eastern Davis Sea.

Changesin sea ice extent, thickness and/ord uration affect both the timing and magnitude of sea ice algal production and phytoplankton production in the Southern Ocean [Smith and Comiso, 2008; Montes-Hugo et al., 2009]. Models indicate that a decrease in sea ice extent may result in an increase in overall marine primary production due to higher light availability in the ice-free areas [Arrigo and Thomas, 2004; Arrigo et al., 2008]. However, other research indicates that a decrease in sea ice may reduce Southern Ocean iron supply and may reduce overall production [Lance lot et al., 2009; Lannuze let al., 2010]. Importantly, a decrease in sea ice extent will result in a reduction in the spring time iceedge algal blooms. While research in the west Antarctic Peninsula region has shown a general decrease in phytoplankton production in relation to decreasing sea ice extent and duration, this response varies significantly along a north-south gradient [Montes-Hugo et al., 2009].

Wildlife and fisheries

Se a ice is a key habitat for Antarc tic marine e c o systems, no tjustin winterbutthroughout the year [Thomas and Dieckmann, 2010]. Some species such as Crabeater seals (Lobodon carcinophagus) breed on the mobile pack ice while others, such as the Weddell seals (Leptonychotes weddellii) Emperor penguins (Aptenodytes and forsten) (Figure 13) rely on stable landfast ice as a breeding platform [Kooyman and Burns, 1999]. Sea ice can act as a barrier separating animals from their food source, and can also affect the food source itself. Adélie penguins (Pygoscelis a deliae) and Emperor penguins must cross many tens of kilometres of coastal landfast 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]. In fact, a close relationship has been shown to exist between annual fast ice extent/trekking distance and Emperor penguin breeding success at Dumont d'Urville Station [Massom et al., 2009].



Figure 13. Emperor Penguin (*Aptenodytes* forsten) mating pair with newly hatched chick. Photo by Jan L Lieser.

A close relationship between winter sea ice extent and the biomass, condition and reproductive success of kill has been demonstrated in the Antar tic Peninsula region and off East Antar tica [Atkinson et al, 2004; Nicol et al, 2000]. Sea ice provides ice algae as a food source forkrill and also serves as a refuge from predation for air-breathing vertebrates, which have difficulty accessing the population during the winter [Flores et al, 2012; Nicol, 2006]. Baleen whales migrating south from their tropic alwintering grounds aggregate along the edge of the pack ice as it retreats in spring, to feed on krill that have spent their winter runder the frozen sea [Nicol et al, 2008]. Changes in sea ice extent are there fore likely to affect ice-associated baleen whale species such as Minke whales (Balae noptera bonae mnsis) and Blue whales (Balae noptera musculus), as well as Orca whales (Orcinus or a).

Changes in sea ice extent in the west Antarctic Peninsula region have also had consequences for the Antarctic krill fishery. In particular, reduced ice cover has allowed increased access to fishing grounds during winter [Kawaguchi et al., 2009; Nicol et al., 2012]. The ecosystem consequences of changes in fishing activity combined with changes in sea ice habitats are somewhat unclear, however [Melbourne-Thomas et al., 2013; Trive lpie ce et al., 2011].

Southern Ocean food webs and the life cycles of many Antarctic marine animals are c losely attuned to the seasonal rhythms of their physical environment, in particular the annualad vance and retreat of sea ice. The sensitivity of Antarc tice cosystems to changing sea ice conditions has become increasingly apparent in recent years. For example, in the west Antarctic Peninsula region, the trend towards reduced sea ice has resulted in population changes for ice-dependent Adélie penguins. Specifically, there is some evidence that populations of these penguins have moved southwards - to be replaced by Gentoo penguins (Pygoscelis papua) and Chinstrap penguins (Pygoscelis antarctica) that previously bred predominantly on northerly sub-Antarctic islands [Mc Clintock et al, 2008]. However, the ecosystem consequences of changes in sea ice habitats on the west Antarctic Peninsula region are complicated [Melbourne-Thomas et al., 2013; Montes-Hugo et al, 2009; Tive lpiece et al, 2011], and it is unlikely that observations made in this region can be extrapolated to other regions of the Southern Ocean. Regionally-specific process and modelling studies, and importantly long-term and coordinated observations, are needed to understand and predict the impacts of changing sea ice on Antarctic ecosystem structure and function.

FUTURE IMPACTS OF CLIMATE CHANGE ON ANTARCTIC SEA ICE

$Model\,issues\,and\,\,pre\,dic\,tions$

Accurately predicting the future state and distribution of Antarctic sea ice represents a considerable challenge for climate modellers. Although sophisticated, the current generation of coupled climate models exhibit a wide range of Antarctic sea ice climatologies, with few reproducing the increase in overall sea ice extent observed since the late 1970s [Eisenman et al., 2011; Maksym et al., 2012; Turner et al., 2013b]. Most climate models fail to accurately simulate mean ice extent, particularly in summer, and o ve re stima te its ye ar-to-ye ar va ria bility [$Maksym \ et \ al.$, 2012]. The se factors, which suggest that key processes are being simulated incorrectly and/or neglected, unfortunately undermine the degree of confidence that can be placed in predictions of likely sea-ice conditions over the coming decades [$Tume \ ret \ al.$, 2013a]. They also underline a critical need to carry out coordinated in-situ measurement programs to be tter understand sea ice-atmosphere-ocean processes at play.



Figure 14. Predicted changes in Antarctic sea ice extent and concentration from the Australian Community Climate and Earth System Simulator. Figure courtesy Siobhan O'Farrell (CSIRO).

Neverthe less, c limate models generally predict an overall reduction in Antarctic sea ice by the end of this century, as the effects of greenhouse gas increases become more significant and seasonal influences of stratospheric ozone loss decline (due to recovery of the Antarctic Ozone Hole). Simulations and projections from one model, the Australian Community Climate and Earth-System Simulator or ACCESS model (*Biet al.*, 2013), are shown in Figure 14. An ensemble mean of the IPCC AR4 models suggest that the annual average total sea ice area will decline by a third by 2100 [*Bracegirdle et al.*, 2008]. This retreat is predicted to be greatest in spring and winter when annual ice extent is largest, which would decrease the amplitude of the seasonal cycle of sea ice areal extent. However, current climate models are unable to provide a precise regional (and seasonal) assessment of expected changes [*Lefebvre and Goosse*, 2008; *Tlumer et al.*, 2013a]. In terms of seasonality, *Stammerjohn et al.* [2012] speculate that current trends towards later autumn advance and earlier spring retreat may well continue. Future coverage of fast ice is unknown, as it is not included in global climate models.

Model results suggest that ice thickness may be even more sensitive to climate change than ice extent [*Arzel et al.*, 2006]. In their study of ensemble output from IPCC AR4 coupled climate models, *Sen-Gupta et al.* [2009] showed a robust decrease in average ice thickness and volume across the models for both summer and winter. The multi-model mean further indicates that for the winter season, substantial sea ice loss will occur at all longitudes, with the greatest loss occurring in the western Antarctic - particularly from the outer edge of the Weddell region (0° W to 30° W) and between 90° W and 150° W. In summer, the greatest ice loss is predicted to be to the east of the Antarctic Peninsula. As highlighted earlier, accurate assessments of change in Antarctic sea ice thickness and volume are severely hampered by the lack of base line information [*Maksym et al.*, 2012].

O the r like ly impacts

Predicted increases in wind strength/storminess in summer and autumn in particular [Bracegirdle et al., 2008; Turner et al., 2013a], waviness and snowfall [Bracegirdle et al, 2008; Emoni and Brown, 2005; Meehlet al, 2006] are likely to have a major effect on the future Antarctic sea ice environment, and in a complex fashion [Massom and Stammerjohn, 2010]. Stronger winds and/or greater prevalence of extreme wind events would lead to more ice rafting and ridging and increased ice thickness in some areas (for example Massom et al. [2006]), while greatly affecting the floe size distribution of the sea ice cover. Greater wave energy generated by an increase in storminess would affect the width and characteristics of the marginalice zone and even the characteristics of the inner pack (for example Massom et al., 1999), as well as the breakup of fast ice (particularly when the latter is unprotected by an extensive packice cover, seasonally or otherwise). Fast-ice formation and seasonality are also highly sensitive to wind speed and direction [He il, 2006; Massom et al., 2010]. Ice conditions, especially in bays, will be sub stantially different in a climate with different wind patterns than at present. The breakup or enhanced melt of fast ice could, however, be counterbalanced by the increased discharge of icebergs since grounded icebergs act as key anchor points for fast ice formation in many locations [Giles et al, 2008]. Increased sheet discharge (potential iceberg production) is predicted to occurunderwarming conditions [Bentley et al, 2007].

Impact of increased snow

Increased snow accumulation on sea ice could potentially lead to an increase in surface flooding by depressing the ice surface below sea level and warming the ice (a warmer ice coveris more permeable to the passage of seawater through it [Golden et al, 1998]). In this way, increased snowfall could lead to enhanced formation of snow ice [Fichefet and Morales Maqueda, 1999]. This can be a more efficient means of ice thickening, given that freezing occurs on the ice surface rather than the base [Lytle and Ackley, 2001]. In other words, enhanced snow ice formation could maintain sea ice thickness to some (unknown) extent by counterbalancing any increase in ice basal melting under ocean warming conditions [Maksym and Markus, 2008; Wu et al., 1999].

At the same time, the presence of a thickersnow covercould delay the summerice melt due to its high a lbe do - to potentially lengthen the sea ice season in certain regions [Eicken et al., 1995; Le dle y, 1991]. Another potential impact of greatersnow accumulation is an increase in freshwater flux into the ocean when the ice melts, leading to increased ocean surface stratification. This could in turn lead to reductions in the upward flux of ocean heat for basal sea ice melt, implying that sea ice duration and extent may actually increase under warming conditions (for example Zhang [2007]). These potential scenarios once again underline the complexity of the sea ice-ocean-atmosphere interaction system.

FUIURE CHALLENG ES

Improving the performance of models

In spite of major advances in our understanding of Antarctic sea ice over the past three decades, there is still much to be learned about its characteristics; its interactions and connections with the atmosphere, ocean and ecosystem; and its complex response to, and role in, present and future climate change [Maksym et al, 2012]. A key challenge is to improve the performance of numerical models in simulating recent, and predicting future, Antarctic sea ice distribution and state, and to include seasonal and regional sensitivities in the models [Maksym et al, 2012; Tumer et al, 2013a]. Improved parameterisation and understanding of change and variability not only requires more and improved observations. It also necessitates identification and better understanding of processes and mechanisms involved. These include ocean forcing and feedbacks [Russe ll et al., 2006], as well as the role that sea ice itself may play in modulating the response to external (atmospheric and oceanic) forcing [Raphaelet al., 2011; Maksym et al., 2012].

Estimating sea ice thickness

A major stumbling block at present is our lack of knowledge of the current distribution of the thickness of Antarctic sea ice and its snow cover, and of how these are changing and what processes are involved; that is, the relative contributions of dynamic and the modynamic processes (including snow-ice formation). The ice thickness distribution provides an integrated measure of total sea ice production and, thus, total oceanatmosphere heat loss, the surface salinity flux in winter and freshwater input into the ocean

SEALS, POLYNYAS AND A 30-YEAR-OLD MYSTERY OF THE DEEP

Scientists believed that the cold, dense bottom waters of the global ocean originated at three different locations in Antarctica - the Weddell Sea, the Ross Sea and the Adélie Coast of East Antarctica. Thirty years ago, a fourth source was speculated to exist somewhere in the Prydz Bay region, but until now scientists have been unable to confirm if, where and how it is being formed.

Now, through sophisticated satellite data, oceanographic moorings and tagged seals, a team involving ACECRC researchers has discovered that a fourth stream of "Antarctic Bottom Water" (AABW) is being produced from intense sea ice formation in the Cape Damley Polynya (65° E-69° E, 67.5° S), north-west of the Amery Ice Shelf. Oshima et al. [2013] estimate that this source of AABW represents between 6% and 13% of the circumpolar total. Its significance is underlined by the fact that AABW is a key driver of the global ocean circulation and therefore of the Earth's climate.

Data collected by instrumented Southern elephant seals allowed scientists to pinpoint the path of the dense salty water and therefore identify the area from which it originates. This oceanographic data collected by the seals is part of a larger ecological project at Institute for Marine and Antarctic Studies (IMAS) to study their behaviour. When the seals surface, their instrument tags relay information (via satellite) back to land, where it is collected by the Integrated Marine Observing System (IMOS). The newly identified source of AABW is different from the other three sources. Its existence demonstrates that polynyas are capable of forming sufficiently dense Shelf Water over a narrow section of continental shelf without the traditional assistance of a large ice shelf or coastal storage volume. This opens the possibility for further discoveries of AABW production from the other polynya regions around the Antarctic coastline.



Salinities at bottom-of-dive for all available ocean temperature and salinity profiles measured by instrumented seals over the continental shelf off Cape Damley and in Prydz Bay where the bottom depth was >250m and potential temperature <1.7 °C. All other dive locations are indicated by small grey points. From *Ohshima et al.* [2013]. in summer. Current large observational uncertainties in these quantities (of 50%-100%) severely compromise the ability to effectively evaluate models - and thus undermine our confidence in the accuracy of future predictions [$Maksym\ e\ t\ a\ l,\ 2012$].

Given these factors, it is critical to derive more accurate baseline information on the thickness and volume of sea ice on regional to circumpolar scales by satellite remote sensing. This can only be achieved through effective calibration and validation programs involving careful coordination of *in-sitU* observations with coincident satellite, airborne and underice remote sensing (for example *Lie sere tal* [2011, 2013], *Williams et al* [2013]). This in itself represents a considerable challenge, given the range of scales involved. Other key challenges to the derivation of sea ice thickness information from satellite altimetry (both laser and madar) are the relatively small freeboard of Antarctic (compared to Arctic) sea ice, the widespread (though as yet unquantified) occurrence of surface flooding, and the need for accurate independent information on snow thickness and density and ice density [*Gile s et al.*, 2008a; *Maksym and Markus*, 2008].

O the r c halle ng e s

Clearly, improved knowledge of the precise mechanisms involving, and feedbacks between, snowfall, ice growth and melt, and upper-ocean stability (stratification) and vertic alle attransportiscritic alforunderstanding the current behaviour and characteristics of Antarctic sea ice and its future trajectory [$Maksym\ et\ al.$, 2012]. This again represents a considerable challenge, given the complexities and regional and seasonal sensitivities involved. Fortunately, we are on the cusp of an exciting new era in observational capability for monitoring the Antarctic sea ice environment, using autonomous drifting and ice-te there d platforms [$Maksym\ et\ al.$, 2012]. These can provide continuous, season-long observations of atmosphere-ice-ocean interactions and the evolution of the sea ice and its snow cover that have been largely lacking to date. While such platforms have the potential to revolutionise our understanding of the severely under-sampled Antarctic sea ice zone, relatively few have been deployed to date. The challenge is again to step up deployment, but in a coordinated fashion around Antarctica (including on fast ice and in the marginal ice zone).

Given the rapid decline in Arctic sea ice and our uncertain knowledge of Antarctic sea ice, there is strong impetus for process studies and more sustained integrated observations that span disciplines and a range of space and time scales. The continuation of fieldbased observations using icebreakers is crucial in this respect [Maksym et al, 2012].

STRATEGIC FOCUS

The Intergovernmental Panelon Climate Change concluded in its Fifth Assessment Report [*IPCC*, 2013] that the observed warming of the Earth is strongest in the polar regions. Surface temperatures overlarge areas of the Antar tic Peninsula have risen considerably faster than the global average. The Southern Ocean is also warming more rapidly than the global ocean average.

Antarctic and Southern Ocean processes influence weather and climate on both regional and global scales, and impact the wider environment and ecosystems.

The Antarctic sea-ice zone is a major component of the Earth's climate system, and we know that it is changing. As this Position Analysis shows, there are key components of Antarctic sea ice that we know little about. Filling this lack of knowledge of such a vital region of the globe is an important research task for the coming decade.

In recent years, the technology needed to observe the ocean has developed rapidly. The use of this new technology has the potential to reduce the cost of research in the region. Platforms ranging from drifting buoys, to autonomous underwater robots and remotely-operated aircraft can be used to complement traditional (and essential) icebreaker research platforms and aircraft. These on-site fieldwork measurements can be matched with satellite technologies to observe the sea-ice zone on the hemispheric and global scale.

It will be essential to include many different disciplines in this effort, as feedbacks across various regional scales will link into the different spheres of the global system. This research must be integrated with national and international efforts in the region. While satellites can measure sea-ice extent, it will be important to get a measure of and develop methods for predicting sea ice thickness in the entire sea-ice zone of the Antarctic. This new knowledge will support improvements to numerical models of the coupled atmosphere-ocean-cryosphere system, and through this, the predictability of the climate system and, as an extension, also that of ecosystem models.

Australian research is important in understanding impacts arising from changes in Antarctic sea ice, but Australia also has a key role in ensuring that such research is available in relevant forums of the Antarctic Treaty System (ATS), most notably the Antarctic Treaty Consultative Meeting and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

Earlier work by the ACE CRC noted that changes in sea ice are likely to impact on a number of activities within the Antarc tic Theaty area. Reductions in sea ice will reduce 'natural' barriers to shipping access in high latitudes and open up otherwise difficult are as formarine resources harvesting. While these activities are managed under the ATS, Australia has an interest in ensuing that these decisions take account of current science. Australia's commitment to integrated research, for example the two SIPEX voyages (in 2007 and 2012), provides crucially important contributions to international efforts to understand observed and potential changes to sea ice. This research and its outcomes are directly linked to Australian interests and government goals for the Australian Antarc tic Program.

Australia's work on sea ice builds on a lengthy commitment to marine science and Antarctic infrastructure. While such commitments are challenging, Australia will be well served by maintaining capacity and assets in high-latitude marine science with sufficient capacity to undertake winter sea ice expeditions. This means maintaining sufficient icebreaking capacity in its ongoing Antarctic logistics and infrastructure planning, and embracing the use of new technologies that greatly aid measurement and monitoring of the difficult sea-ice environment.

Such investments provide opportunities to work with international partners in challenging environments and to continue a century of scientific endeavour that addresses critical questions and supports management of a region that is of direct interest to Australia.

CONCLUSION

Antarctic sea ice is regarded as a sensitive indicator of climate change. Its presence at the interface between the atmosphere and the ocean in polar latitudes makes it highly susceptible to dynamic and thermodynamic changes and variations from above and below. It responds to changes in the environmental conditions in a complex way. For example, while a warming atmosphere and increased heat content in the ocean will have a thinning effect on the sea ice, greater wind and wave energy can break up sea ice to potentially increase the ice thickness by rafting and ridging.

An increase in snow coveron top of the sea ice will help to the mally insulate the ocean from the atmosphere and therefore reduce freezing rates of sea ice, but at the same time can suppress a thinnerice coverbelow the waterline and facilitate increase in ice thickness by snow-ice formation.

The observed patterns of change in Antarc tic sea ice are manifold and not uniform across the region. While the overall extent of sea ice, for example, shows a slight increasing trend (panela. in Figure 4), there are starkly contrasting trends on oceanic basin scales (Ross Sea versus Belling shausen/Amund sen seas). Similar heterogeneous patterns can be found in maps of trends in sea ice duration/sea sonality (Figures 5 and 6).

Sea ice plays a critical role in biogeochemical cycles and the marine ecosystem in the high-latitude Southern Ocean. The life cycles of many marine animals are closely linked to the seasonal rhythm of the physical environment, and changing sea ice conditions might have beneficial effects for some species, but can be potentially devastating for others.

Recent advances in space-borne remote sensing enable a first assessment of largescale sea ice thickness (and subsequently sea ice volume) based on surface elevation (freeboard) measurements. Such measurements will enable a reliable estimate of sea ice volume over time if carried out in the same area repeatedly with constant precision.

In order to better understand the influence of a changing environment on the geophysical properties of sea ice and flow-on effects on the ice-associated ecosystem, as well as to calibrate and validate established and emerging remote-sensing products, a continued internationally collaborative and inter-disciplinary *in-situ* monitoring and research effort is crucial.



Scientists and support staff at work on East Antarctic sea ice during the second Sea Ice Physics & Ecosystems eXperiment (SIPEX 2) in 2012. Photo by Brian Walpole

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