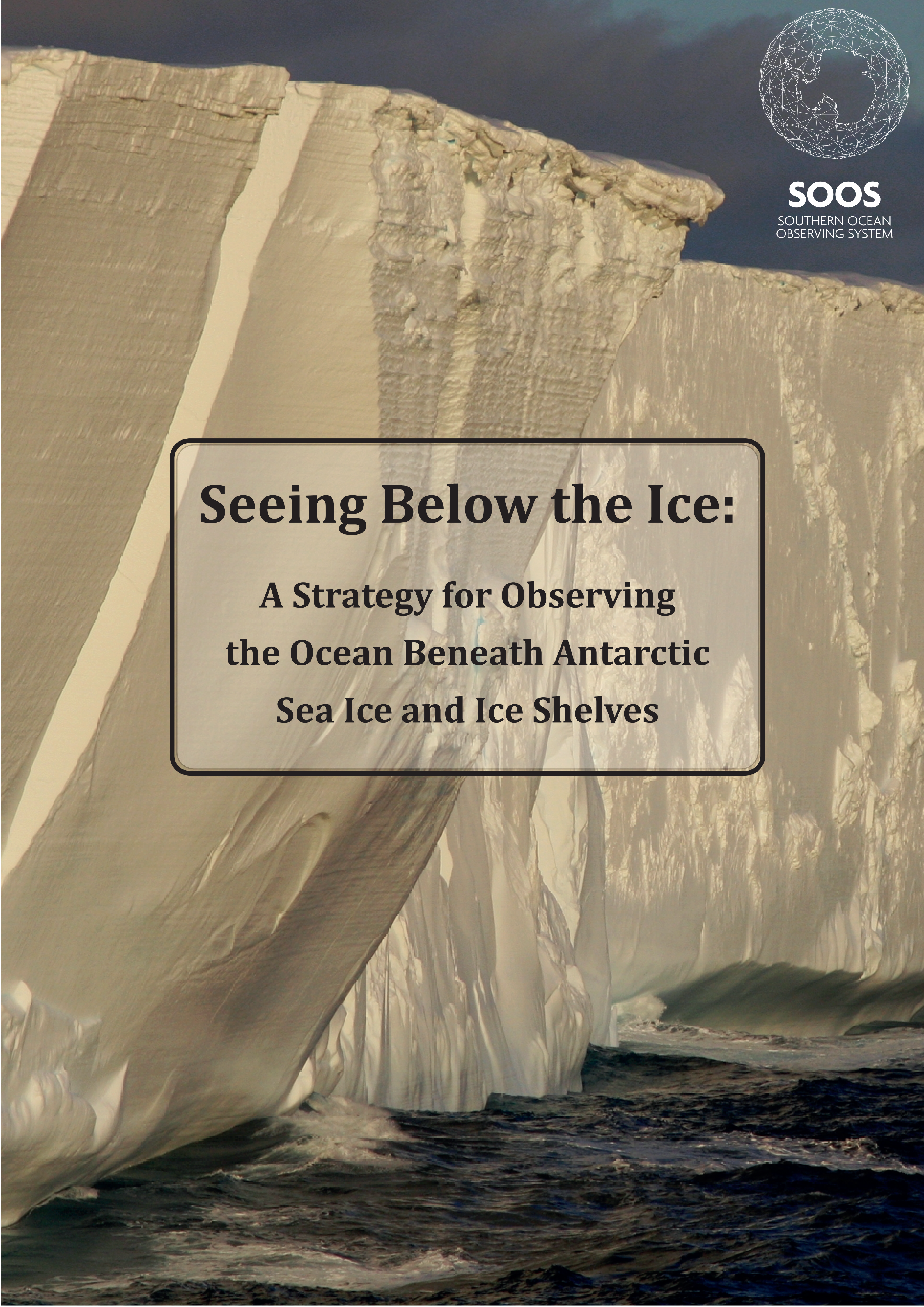

Seeing Below the Ice:

A Strategy for Observing the Ocean Beneath Antarctic Sea Ice and Ice Shelves

SOOS
SOUTHERN OCEAN OBSERVING SYSTEM

Seeing below the ice: A strategy for observing the ocean beneath Antarctic sea ice and ice shelves

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This strategy lays the foundation for Under Ice observations for SOOS and will be revised and updated at regular intervals.

CONTENTS

1. INTRODUCTION

Interactions between the Southern Ocean, atmosphere and cryosphere influence climate, biogeochemical cycles and biological productivity on global scales. However, many key high latitude processes remain poorly understood because of a lack of observations. The ocean beneath Antarctic sea ice and ice shelves is likely the least well observed physical system on the planet. Antarctic sea ice expands from a late summer low of around 4 $x10^6$ km^2 to a maximum extent of 19 $x10^6$ km^2 during late winter/spring. Antarctic ice shelves cover a further 1.5 million square kilometres. This under-ice "blind spot" in the global ocean observing system is a major impediment to better understanding of climate, biogeochemical cycles and sea level rise.

Measurements of the ocean beneath Antarctic sea ice are sparse because traditional oceanographic tools are not suitable for sustained measurements in ice-covered seas. The only way to reach the ocean beneath the floating glaciers of Antarctica is by drilling through the glaciers from above, or by sending autonomous submarines into the ice shelf cavities, both technically and logistically challenging. Ice-breaking vessels can operate in sea ice, but with difficulty and at great expense. Satellite sensors cannot see the ocean beneath the ice and persistent cloud cover limits the utility of satellite instruments that use the infrared and visible parts of the spectrum. When sea ice is present, profiling floats cannot surface to transfer data or obtain a position. Surface moorings are not feasible in the sea ice zone due to the high likelihood of damage by ice.

New technologies now allow ocean measurements to be made in the Antarctic sea ice zone and beneath ice shelves. These tools include floats adapted for profiling under ice, profilers tethered to ice floes or deployed through boreholes in floating glaciers, subsurface moorings, acoustic navigation of floats and gliders under the ice, advances in data telemetry, deployment of oceanographic instruments on animals like seals, sampling from unmanned vehicles in the ocean, atmosphere and beneath ice shelves, and new satellite instruments. Technological advances in ocean and under ice observing are developing rapidly and future observing systems will include the enhanced use of data telemetry and pop-up storage capsules, airborne remote sensing, the deployment of inexpensive and expendable bottom temperature and pressure recorders, the deployment of moorings in ice shelf cavities by remotely operated vehicles and enhanced acoustic capabilities across a broader range of frequencies. For the first time, it is feasible to directly measure key ice-ocean-atmosphere interactions in Antarctica that regulate global climate, sea level rise and biogeochemical cycles.

The idea for an Under Ice strategy outlining the design of an under ice observing system began with discussions about the feasibility of extending the Argo array into the high latitudes. This was supported by the Argo Science Team and broadened in scope to include the consideration of other platforms and a broader vision of the under-ice zone to include sea ice, ice shelves and ocean and atmospheric interactions. The need for a strategy for under-ice observations was also strongly endorsed by the Southern Ocean Observing Sysem (SOOS, **www.soos.aq**).

An international workshop supported by the CSIRO Wealth from Oceans Flagship and SOOS was held in Hobart, Tasmania in October 2012. The Antarctic under-ice zone is defined here to extend from the northern limit of the winter sea ice edge to the grounding line, the transition point between the grounded ice sheet and the floating ice shelf. The workshop focused on measurements of the ocean beneath the Antarctic ice, both sea ice and ice shelves, including the observations of sea ice, glacial ice and the atmosphere needed to improve our understanding of interactions between the ocean, the atmosphere and the cryosphere. While there was a strong emphasis on sustained observations, it was recognised that process studies are also essential, and in many cases there is strong synergy between the two types of observations.

This report outlines a strategy for observing the ocean under Antarctic sea ice and ice shelves. Section 2 provides a brief summary of the scientific background and motivation for under ice observations, organised under three themes: Circulation and inventories of heat, freshwater and carbon in the sea ice zone; Ocean – sea ice interaction; and Ocean – ice shelf interaction. Section 3 summarises the objectives and key scientific questions in each theme, questions that cannot be addressed without an expanded under-ice observing system. An integrated sampling strategy is outlined in Section 4. The path to implementation is described in Section 5 and the key recommendations are summarised in Section 6.

2. BACKGROUND AND MOTIVATION FOR AN UNDER-ICE OBSERVING SYSTEM

Southern Ocean processes influence climate, biogeochemical cycles and biological productivity on global scales. The Antarctic Circumpolar Current links the major ocean basins and is the primary means of exchange between them. Water mass transformations in the Southern Ocean connect the deep and upper limbs of the global overturning circulation. The circulation of the Southern Ocean provides the key connections that allow a global-scale network of ocean currents to exist, a network that ultimately controls the evolution of climate by storing and transporting vast quantities of heat, freshwater and carbon dioxide (Figure 1).

Integrated around the globe, the vigorous overturning circulation in the Southern Ocean transfers more heat and anthropogenic carbon dioxide into the ocean interior than any other latitude band (Khatiwala et al., 2009, 2013; Levitus et al., 2012; Rintoul, 2011). Upwelling of deep water transfers carbon dioxide from the ocean to the atmosphere, while sinking of surface waters in the downwelling branches of the overturning circulation transfers carbon dioxide from the atmosphere to the ocean interior (Sabine et al., 2004; Sallée et al., 2012). The balance between these two carbon fluxes determines the strength of the Southern Ocean sink of carbon dioxide (Le Quéré et al., 2007). Upwelling of deep water also returns nutrients to the surface ocean. Export of these nutrients from the Southern Ocean in mode and intermediate waters supports three quarters of marine primary production north of 30°S (Sarmiento et al., 2004).

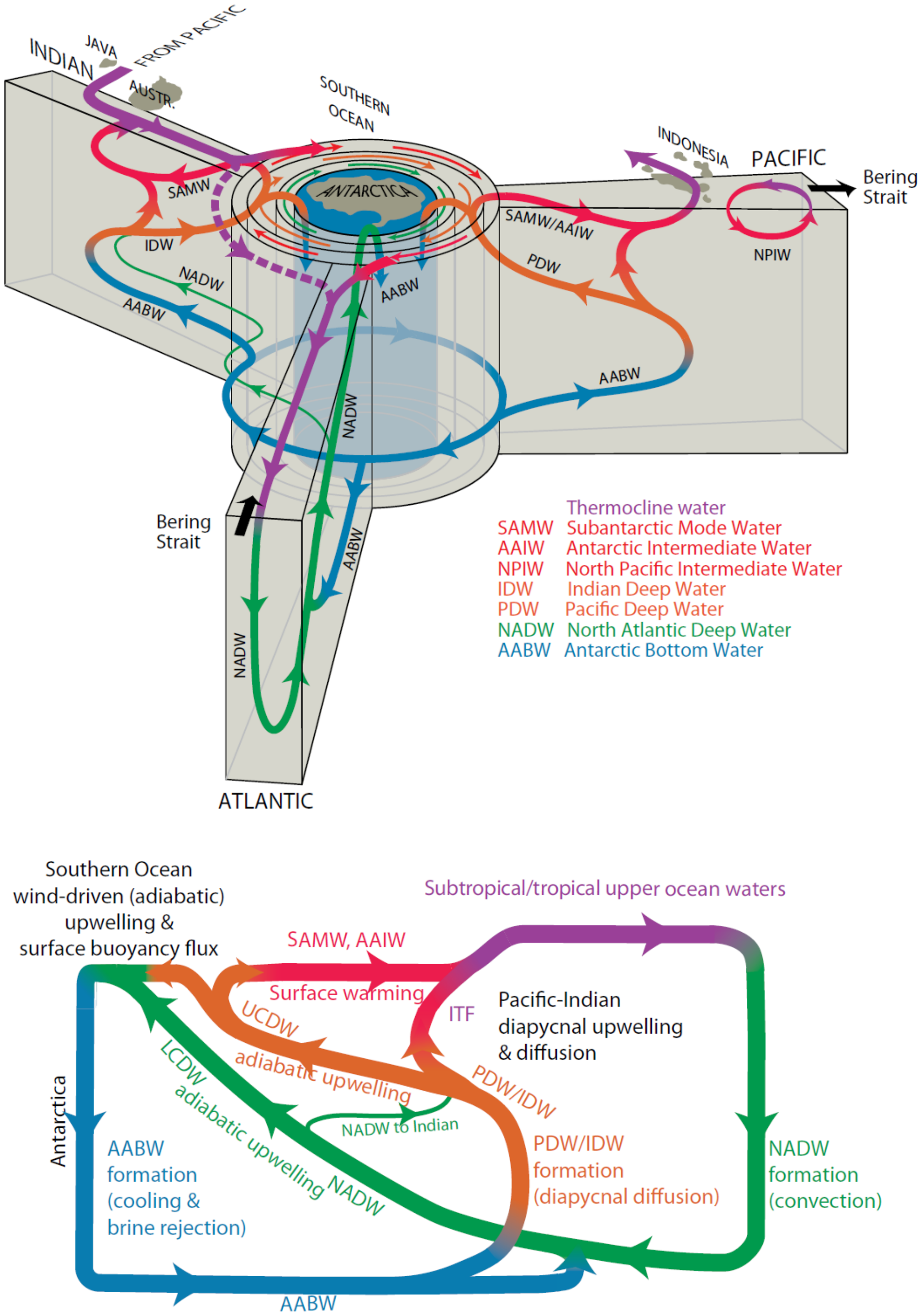


Figure 1: Two schematic views of the global overturning circulation. The Southern Ocean plays two key roles in the global overturning: (1) the Antarctic Circumpolar Current connects the ocean basins, establishing a global-scale overturning circulation, and (2) atmosphere-ocean-ice interactions drive water mass transformations that help close the

global overturning. (From Talley (2013), following Gordon (1986), Schmitz (1995) and Lumpkin and Speer, 2007)).

The expansion of Antarctic sea ice from a summer minimum of 4 x 10^6 km^2 to a winter maximum of 19 x 10^6 km^2 is one of the most dramatic seasonal phenomena on Earth (Figure 2). Antarctic sea ice influences the albedo and hence the energy budget of the planet. Sea ice also influences climate and biogeochemical cycles by driving ocean circulation and regulating air-sea exchange of momentum, heat and gases, and is a key biologically- and biogeochemically-active substrate.

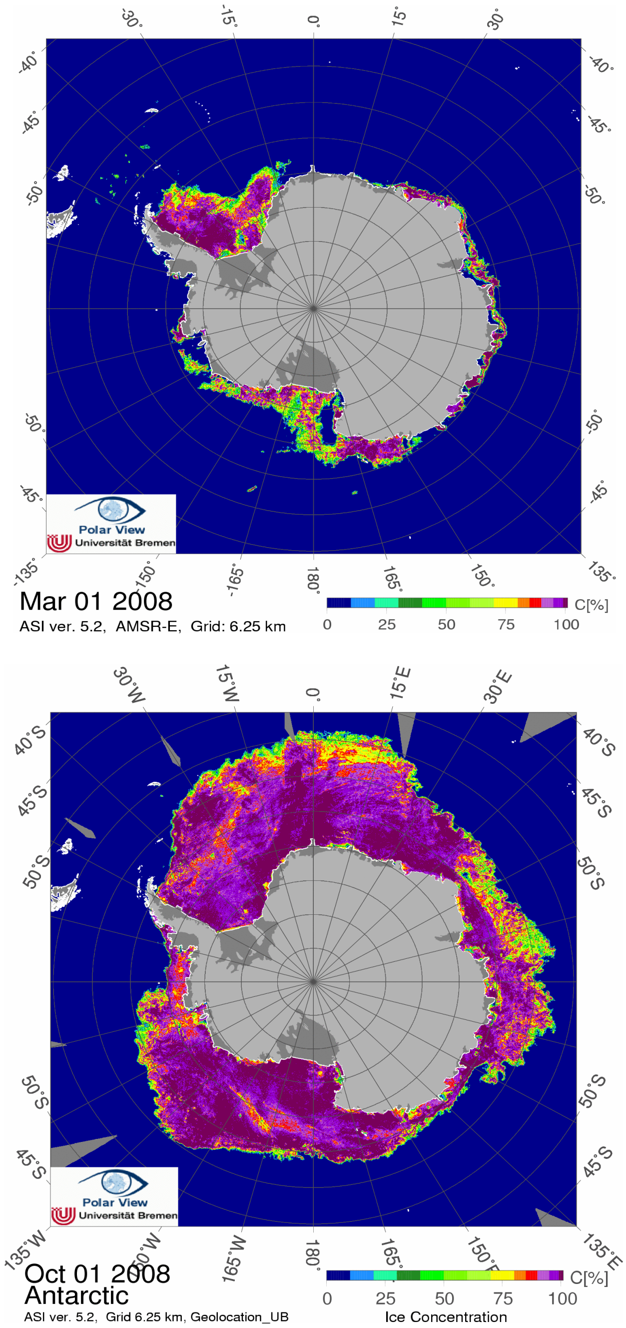


Figure 2: Antarctic sea ice extent in summer (March 1, 2008; top) and winter (October 1, 2008; bottom). The total area covered by Antarctic sea ice expands from about 4 x 10^6 km^2

in summer to about 19 x 10⁶ km² in winter, an increase larger than the area of the Arctic Ocean (Source: AMSR-E, Bremen.)

Difficulty in predicting the future behaviour of the Greenland and Antarctic ice sheets contributes the largest uncertainty to estimates of future sea level rise (Vaughan et al., 2013). The mass balance of the ice sheet is determined by the rate of input by snowfall and the loss due to iceberg calving and basal melt of floating ice shelves. The role of the ocean in regulating the loss of ice has received growing attention in the last decade. The huge capacity of the ocean to store heat means that changes in ocean temperature or circulation can substantially alter the basal melt rate of floating ice (Rignot and Jacobs, 2002; Pritchard *et al*., 2012). In particular, thinning of ice shelves as a result of enhanced surface or basal melt can reduce the buttressing effect of the ice shelves, accelerate the flow of glacial ice to the sea, and raise sea level. Ocean melting may also drive retreat of the grounding line and increase the susceptibility of the marine-based ice sheet to unstable retreat, in which thinning and retreat of the grounding line (on a bed sloping down towards the interior) leads to increased ice discharge and further thinning and retreat (Schoof, 2007).

Interactions between the ocean, atmosphere and cryosphere at high southern latitudes are therefore central to global climate, biogeochemical cycles, biological productivity, and sea level (Figure 3). However, understanding of these coupled interactions remains poor because of the lack of observations . For example, in the Southern Ocean Data Base (Orsi and Whitworth, 2005), there are only 1400 oceanographic profiles south of 60°S in winter; all but 330 of these are from the Antarctic Peninsula or the Weddell Sea. This massive blind spot in the global ocean observing system is a major impediment to better understanding of climate, biogeochemical cycles and sea level rise.

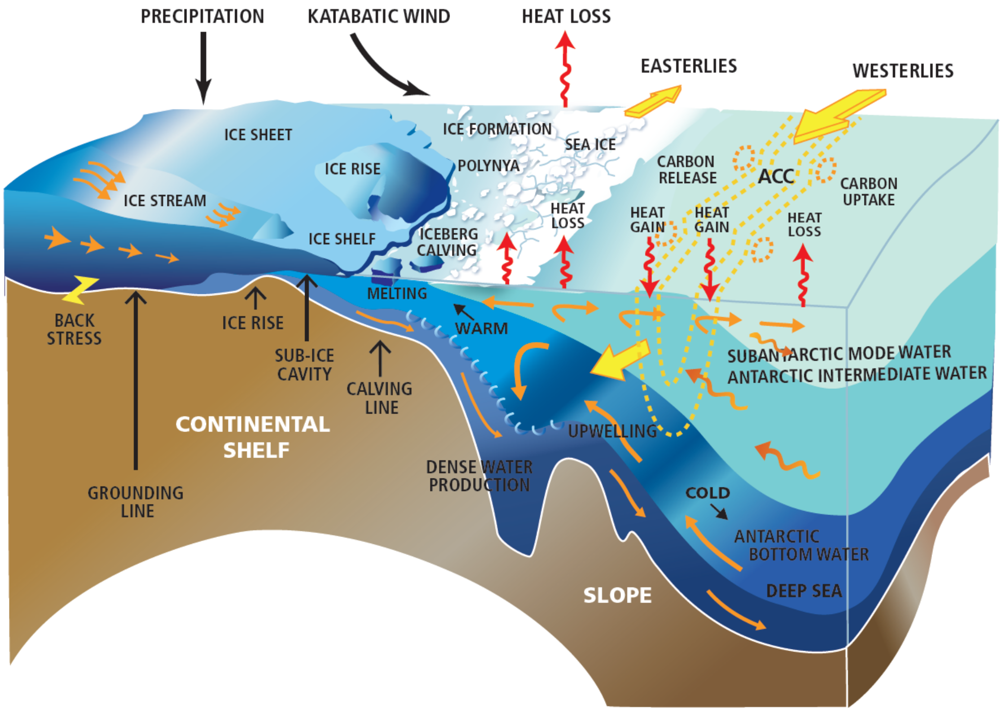


Figure 3: Key physical processes affecting the Antarctic margin,sea ice zone and Southern Ocean. (National Research Council 2011).

In the following, we motivate the need for an under ice observing system in Antarctica and the Southern Ocean by addressing three themes: **Circulation and inventories of heat, freshwater and carbon in the sea ice zone**, **Ocean – sea ice interaction**, and **Ocean – ice shelf interaction**. Progress in each of the themes requires sustained observations of the ocean beneath the ice, although a different sampling strategy is needed for each.

Theme 1: Circulation and inventories of heat, freshwater and carbon in the sea ice zone

Recent studies have revealed wide-spread changes in Southern Ocean temperature and salinity (Figure 4). In the circumpolar average, the Southern Ocean has warmed throughout the upper 2000 m in recent decades (Gille, 2008; Böning et al., 2008). While much of the warming and increase in sea surface height can be explained by a southward shift of the Antarctic Circumpolar Current (Gille, 2008; Sokolov and Rintoul, 2009), changes in air-sea fluxes have likely also contributed (Meijers et al., 2011). The Southern Ocean has also freshened in the upper 2000 m (Böning et al., 2008), possibly linked to increased precipitation (Durack and Wijffels, 2010) and ice melt (Helm et al., 2010). However, observations with sufficient temporal and spatial coverage to track the evolving inventory of heat and freshwater content (in the upper 2000 m) have been made only in the last decade, when Argo floats were deployed in the Southern Ocean. Coverage is still poor in the sea ice zone, where ice cover increases the risk of damage to instrumentation and prevents surfacing of profiling floats. As a consequence of inadequate sampling, estimates of change in global ocean heat content differ most strongly in the high latitudes of the Southern Hemisphere (Rhein et al., 2013). Improved sampling of the Southern Ocean is essential to narrow uncertainties in the planetary energy budget (Durack et al., 2014) and to determine the relative contributions of precipitation, glacial ice melt, and sea ice to the freshwater budget.

Dramatic changes have also been observed in the deepest Southern Ocean waters in recent decades. Warming of Antarctic Bottom Water (AABW) has been observed throughout much of the ocean, contributing about 10% of the total thermosteric sea level rise (Figure 5; Purkey and Johnson, 2010). AABW has also freshened and contracted (Aoki et al., 2005; Rintoul, 2007; Jacobs and Giulivi, 2010; Purkey and Johnson, 2013), equivalent to a loss of approximately 8 Sv from the AABW layer (Purkey and Johnson, 2012). van Wijk and Rintoul (2014) show that the volume of the AABW layer has declined by about 50% since the 1970s in the Australian Antarctic Basin. The observed changes in potential temperature, salinity, density, volume, and oxygen of AABW can be accounted for by freshening of the source waters but cannot be explained by changes in formation rate alone (van Wijk and Rintoul, 2014). Quantifying and attributing changes in the deep ocean to interior processes or surface forcing remains a difficult challenge, however, as observations in the ice-covered formation zones are scarce and mostly limited to a small number of repeat hydrographic sections.

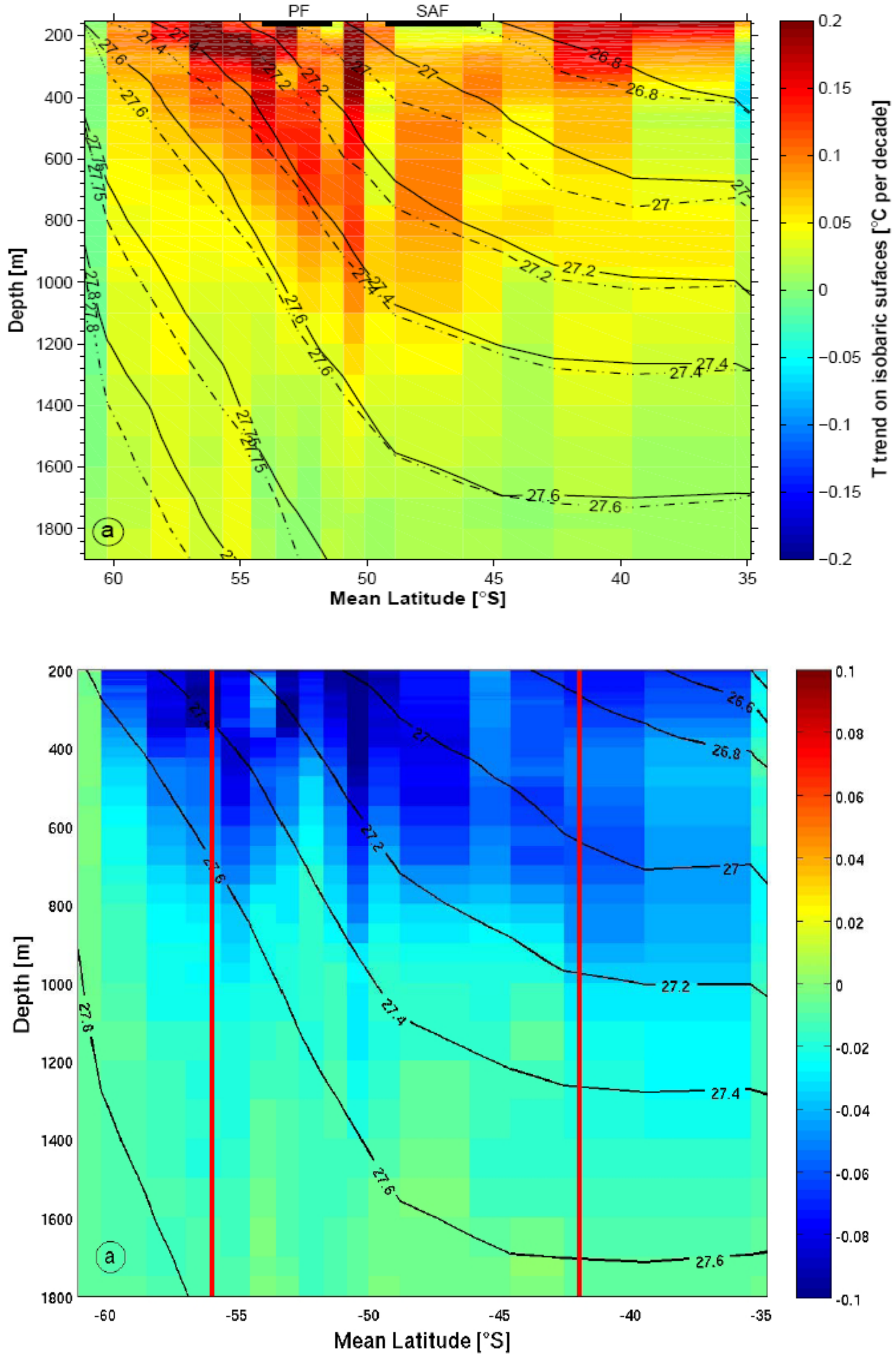


Figure 4: Temperature trends (top, ºC per decade*) and salinity trends (bottom*, psu per decade*) in the Southern Ocean. The Southern Ocean has warmed and freshened throughout the upper ocean (200 to 1800 m). Trends are calculated by comparing recent measurements from Argo to a long-term climatology along mean streamlines. Red lines in the lower plot indicate the approximate northern and southern limits of the Antarctic Circumpolar Current (Böning et al., 2008).*

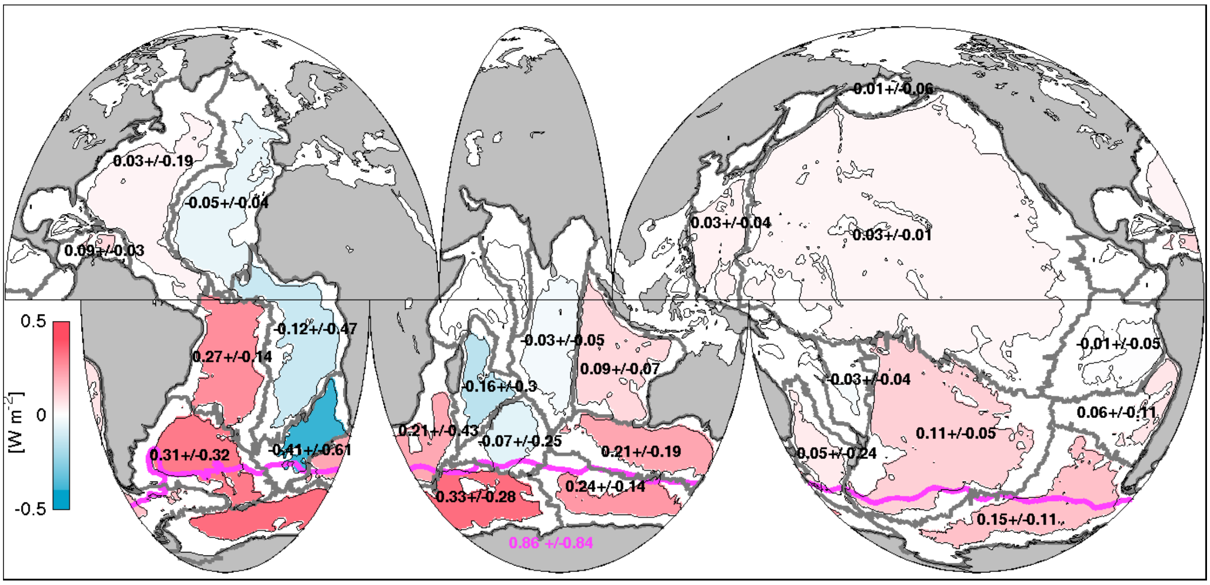


Figure 5: Warming of the abyssal ocean. Temperature change in the Antarctic Bottom Water layer (potential temperature < 0°C) is expressed as an equivalent heat flux (W m^{-2}). The strongest warming signals are observed near Antarctica and along the flow paths that carry AABW northward (Purkey and Johnson, 2010).

Many of the observed changes in the Southern Ocean, including the sea ice changes discussed below, can be linked to changes in wind forcing. The westerlies have shifted south and strengthened, associated with a trend towards the positive phase of the Southern Annular Mode (SAM) (Marshall, 2003; Yang et al., 2007) (Figure 6). The southward shift of the ACC has been attributed to the southward shift in the westerlies (Gille, 2008). The positive trend in the SAM may have also had an impact on the overturning circulation (Figure 7). The strengthening trend in the SAM would be expected to intensify the overturning circulation, but eddy fluxes may counter-act this tendency (Marshall and Speer, 2012). Whether or not they do depends sensitively on the vertical structure of wind and eddy-driven flows (Morrison and Hogg, 2013; Speer et al., 2000). The response of the overturning circulation to changes in wind and buoyancy forcing remains a topic of debate (Rintoul and Naveira Garabato, 2013). The issue is important for climate and global biogeochemical cycles, as increased upwelling of carbon-rich deep water may decrease the effectiveness of the Southern Ocean sink of carbon dioxide (Le Quéré *et al*., 2007). More complete observations of the evolving inventory of temperature, salinity, oxygen, carbon and transient tracers are needed to detect changes in the overturning circulation.

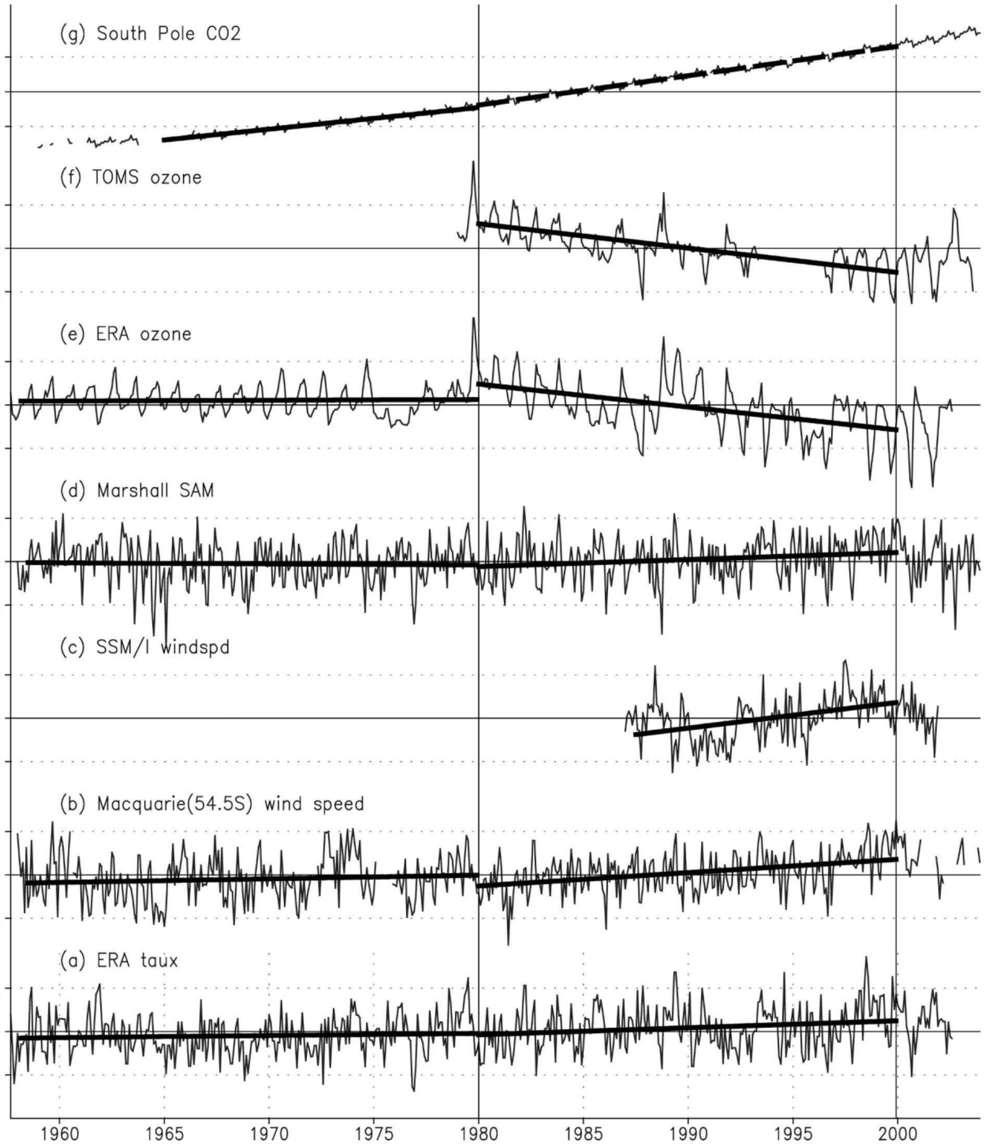


Figure 6: Normalized time series (thin line) and their linear trends (thick line): (a) ERA-40 zonal wind stress over the Southern Ocean (45°–60°S), September 1957–August 2002; (b) in situ observations of wind speed at Macquarie Island (54.5°S, 158.9°E), January 1958–December 2003; (c) the SSM/I satellite wind speed data, January 1987– December 2001; (d) the Marshall Southern Annular Mode index based on the observational SLP data, January 1958–December 2003; (e) ERA-40 Antarctic (60°–90°S) total column ozone, September 1957–August 2002; (f) TOMS satellite Antarctic (60°–90°S) total column ozone, January 1979–December 2003; and (g) atmospheric CO2 concentrations at South Pole (89°59S, 24°48W), September 1957–December 2003. (Note that all trends are calculated from a 13-month running mean of respective time series, which can reduce the sensitivity of trend value to marginal effects. Two separate periods: pre-1980 and January 1980–December 1999 are chosen for the linear trend analysis.) (Yang et al., 2007)

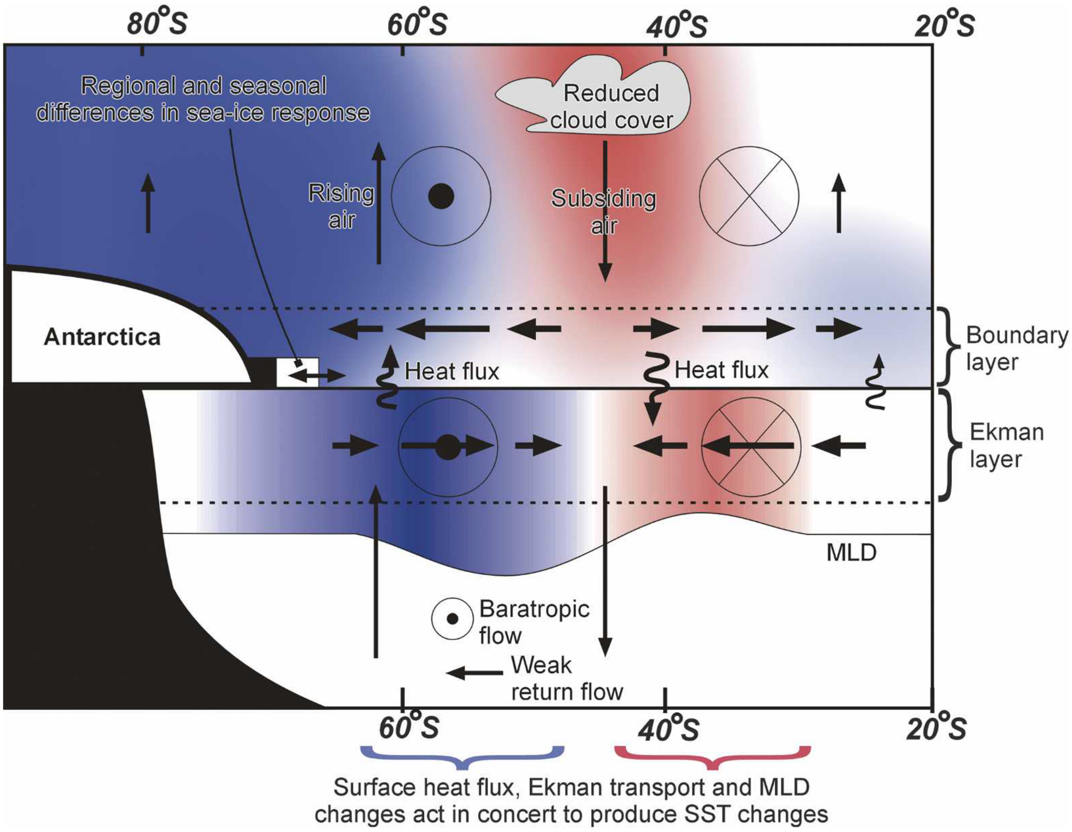


Figure 7: Schematic representation of the effect on the climate system for a positive SAM. The schematic of circulation, properties and fluxes for the negative phase of the SAM exhibits the same patterns as displayed above, only with reversed directions of circulation and the opposite sign for property anomalies and fluxes. (Sen Gupta and England, 2006).

Major ocean circulation features within the sea ice zone include the sub-polar gyres, the Antarctic slope front and coastal currents, deep boundary currents, circulation on the continental shelf, and the flow in sub-ice shelf cavities. All of these ocean current systems are poorly observed. In particular, few observations have been made beneath sea ice or underneath ice shelves. Mean transports are uncertain and even less is known about the sensitivity of the currents to changes in natural or anthropogenic forcing. The gyres, coastal currents, boundary currents and eddy field south of the ACC regulate meridional exchange of mass, heat and freshwater between the open ocean and the continental shelf. This exchange, in turn, influences upper ocean stratification, the distribution of sea ice, the formation and export of dense shelf water, and heat supply to ice shelves. Discharge of glacial melt water from Antarctica may drive rapid changes in stratification, sea level and ocean circulation (e.g. Hellmer, 2004; Rye et al., 2014). Sustained, year-round observations of ocean currents in the sea ice zone are needed to determine how and why the high latitude circulation changes with time and to assess the consequences of change for climate and sea level.

Air-sea fluxes of momentum, heat, freshwater and carbon in the sea ice zone are also poorly observed and highly uncertain (Bourassa et al., 2013). Lack of knowledge of atmospheric forcing provides another obstacle to dynamical understanding of the high latitude ocean circulation, water mass formation, and ocean – ice interaction. Atmospheric models suffer from biases in high southern latitudes that may introduce errors in flux products derived from global atmospheric reanalyses. In situ observations are needed to identify and quantify errors in flux products derived from models or satellites and to improve flux parameterizations. Sustained measurements of ocean heat and freshwater contentwill also help constrain air-sea flux estimates.

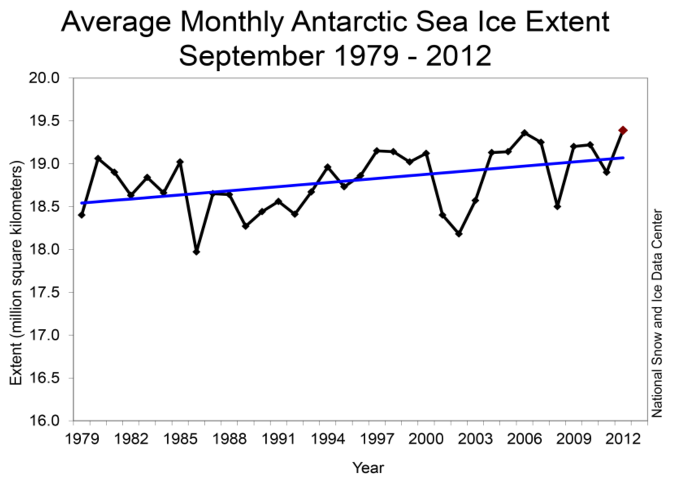
Theme 2: Ocean – sea ice interaction

Antarctic sea ice affects climate, biogeochemical cycles and biological productivity. The presence of sea ice increases the albedo of the Earth, affecting the planetary energy budget. Sea ice cover modulates the exchange of heat, momentum and gases between the ocean and atmosphere. Brine released during sea ice formation drives production of dense shelf water and freshwater released during sea ice melt influences ocean stratification and circulation. Gases released during sea ice formation affect the composition of the atmosphere and the deposition of chemical compounds such as mercury. The ocean and sea ice are coupled to floating glacial ice around the margin of Antarctica: ocean heat flux drives glacial melt (a process influenced by sea ice) and glacial meltwater in turn affects ocean circulation and sea ice distribution. Sea ice cover influences the light and nutrient environment of the upper ocean and hence biological productivity; indeed, sea ice is a critical component of the Antarctic ecosystem, providing habitat, refuge, and a source of food or nutrients for many dependent species.

Despite its importance in the global system, much remains unknown about Antarctic sea ice. The processes controlling the mass, properties, distribution and seasonality of sea ice remain poorly understood. In situ observations are scarce, particularly in winter, and some key properties like sea ice thickness remain essentially unobserved. Satellite measurements have documented the seasonal and interannual variability of sea ice extent and concentration, but do not yet provide information on the thickness of the ice and its overlying snow cover. Satellite observations also cannot directly resolve the coupled interactions between the ocean, atmosphere and sea ice that shape the sea ice cover.

Enhanced observations of sea ice and its interactions with the atmosphere and ocean are essential to improve understanding of this critical part of the Earth's climate system and our ability to project future changes and their impacts. For example, the fact that the overall extent of Antarctic sea ice has increased in recent decades (Turner et al., 2009; Parkinson and Cavalieri, 2012), in stark contrast to the rapid decline in the Arctic, is not yet fully understood (Figure 8). The slow increase in overall extent masks regional changes in the extent and seasonal duration of sea ice that rival those observed in the Arctic, with retreat of ice in the Bellingshausen – Amundsen Seas and expansion of ice in the northwestern Ross Sea

(Stammerjohn et al., 2008) (Figure 9). The regional changes in sea ice likely reflect both changes in wind forcing (Holland and Kwok, 2012) and ocean – ice feedbacks. The ice albedo feedback influences the retreat of sea ice in spring, while ocean thermal feedback may enhance or retard the expansion of sea ice in the autumn (Stammerjohn et al., 2012; Goosse and Zunz, 2014). The rate of sea ice melt or formation is sensitive to ocean heat flux, and hence to the stratification of the upper ocean. Changes in the freshwater balance arising from changes in precipitation, redistribution by sea ice formation, circulation and melt, or input of glacial melt-water (Bintanja et al., 2013; Swart and Fyfe, 2013) can therefore influence the distribution of sea ice. Sea ice distribution and the circulation of the underlying ocean are also sensitive to changes in remote forcing. Li et al. (2014), for example, have linked the expansion of overall Antarctic sea ice extent to surface warming of the tropical and North Atlantic, while variability in the Amundsen Sea Low has been linked to the Southern Annular Mode (Turner *et al.,* 2009) and teleconnections to the tropical Pacific (Steig *et al*., 2012). Changes in storminess and wave climate may also contribute to observed regional changes in Antarctic sea ice extent (Kohout et al., 2014).



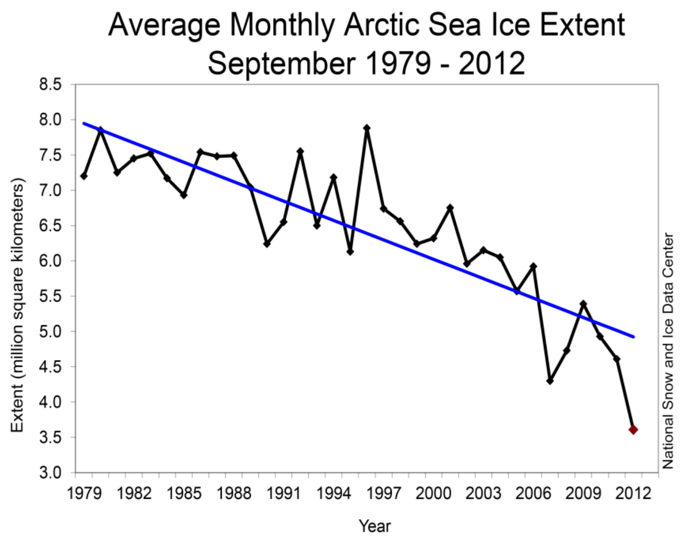


Figure 8: Trends of sea ice extent in September in the Antarctic (top) and Arctic (bottom). (National Snow and Ice Data Center, USA).

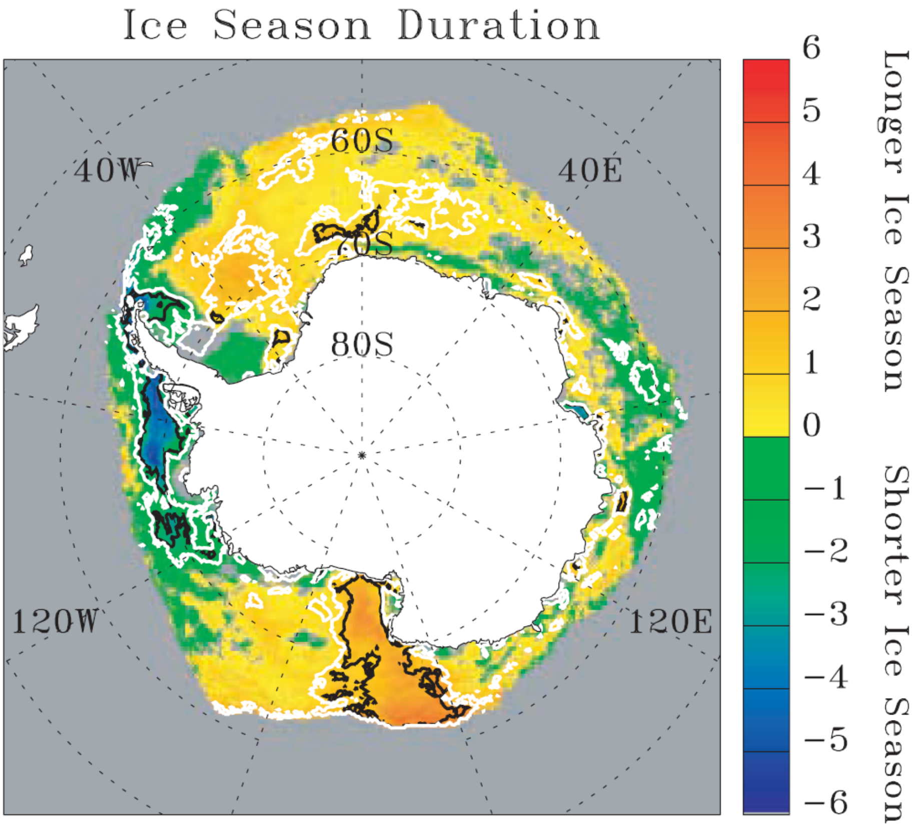


Figure 9: Change in duration of Antarctic sea ice cover (in days yr^{-1}, evaluated between years 1979 and 2004). (Stammerjohn et al., 2008).

Coastal polynyas are of particular interest as sites of intense air-sea interaction and sea ice formation (Massom et al., 1998). About 10% of the total production of Antarctic sea ice occurs in coastal polynyas that occupy less than 1% of the total sea ice area (Tamura et al., 2008). Brine released during sea ice formation in polynyas produces dense High Salinity Shelf Water (HSSW), the precursor to Antarctic Bottom Water. Flow of HSSW into sub-ice shelf cavities drives enhanced basal melt near deep grounding lines (Rignot and Jacobs, 2002). Air-sea interaction in polynyas can also regulate ocean heat transport to ice shelves by altering the temperature and circulation of continental shelf waters (Khazendar et al., 2013). Despite their importance, there are few direct measurements of air-sea interaction and sea ice formation in coastal polynyas and little is known about the sensitivity of coastal polynyas to changes in natural or anthropogenic forcing.

Observations of the interaction of sea ice with the ocean and atmosphere are needed to understand and quantify the physical processes and feedbacks responsible for the mean seasonal cycle of Antarctic sea ice and its sensitivity to climate variability or anthropogenic forcing.

Theme 3: Ocean – ice shelf interaction

A number of recent studies have highlighted the potential sensitivity of the Antarctic Ice Sheet to change in the surrounding ocean (Figure 10; Pritchard *et al*., 2009; 2012). Ocean heat flux melts floating ice shelves from below (Jacobs *et al*., 1992). Thinning or collapse of floating ice shelves reduces their buttressing effect (Dupont and Alley, 2005), leading to more rapid discharge of ice from the continent and an increase in sea level (De Angelis and Skvarca, 2003). However, the physical processes controlling the rate of basal melt remain poorly understood, limiting confidence in projections of future sea level rise.

The West Antarctic ice sheet is losing mass at an accelerating rate, largely in response to oceanic forcing (Joughin *et al*., 2012; Pritchard *et al*., 2009; 2012). Thinning of ice shelves in the Amundsen/Bellingshausen Seas as a result of increased basal melt has reduced their buttressing effect and accelerated glacier flow and ice discharge to the ocean (Pritchard *et al.*, 2009; 2012; Joughin *et al.* 2012). West Antarctic glaciers, including the Pine Island, Smith, Thwaites and Kohler glaciers, are experiencing rapid grounding line retreat, leading to marine ice sheet destabilisation that will significantly contribute to future sea level rise (Joughin *et al*., 2014; Rignot *et al*., 2014). Basal melt is a major contributor to mass loss of the Antarctic ice sheet, with iceberg calving accounting for the remainder (Figure 11; Rignot *et al.*, 2013; Depoorter et al., 2013). Increased calving rates have resulted in higher rates of ice loss by accelerating the flow of glaciers and ice streams over the past few decades (Rignot *et al.*, 2011).

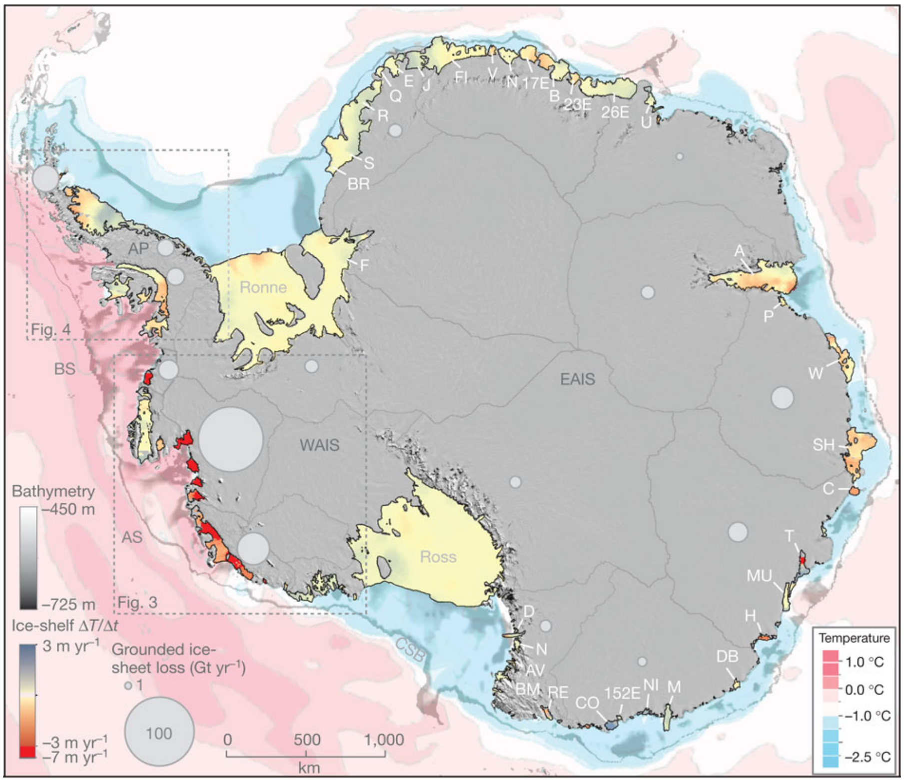


Figure 10: Loss of ice from the grounded portion of the Antarctic ice sheet (in grey circles, with the size of the circle proportional to the magnitude of grounded ice sheet loss). Change in elevation of floating ice shelves and glacier tongues (colours around the edge of the

Antarctic continent). Ocean temperature near the sea floor is shown around the margin of the continent (right hand colour bar). From Pritchard et al. (2012), who conclude "the most profound contemporary changes to the ice sheet and its contribution to sea level can be attributed to ocean thermal forcing."

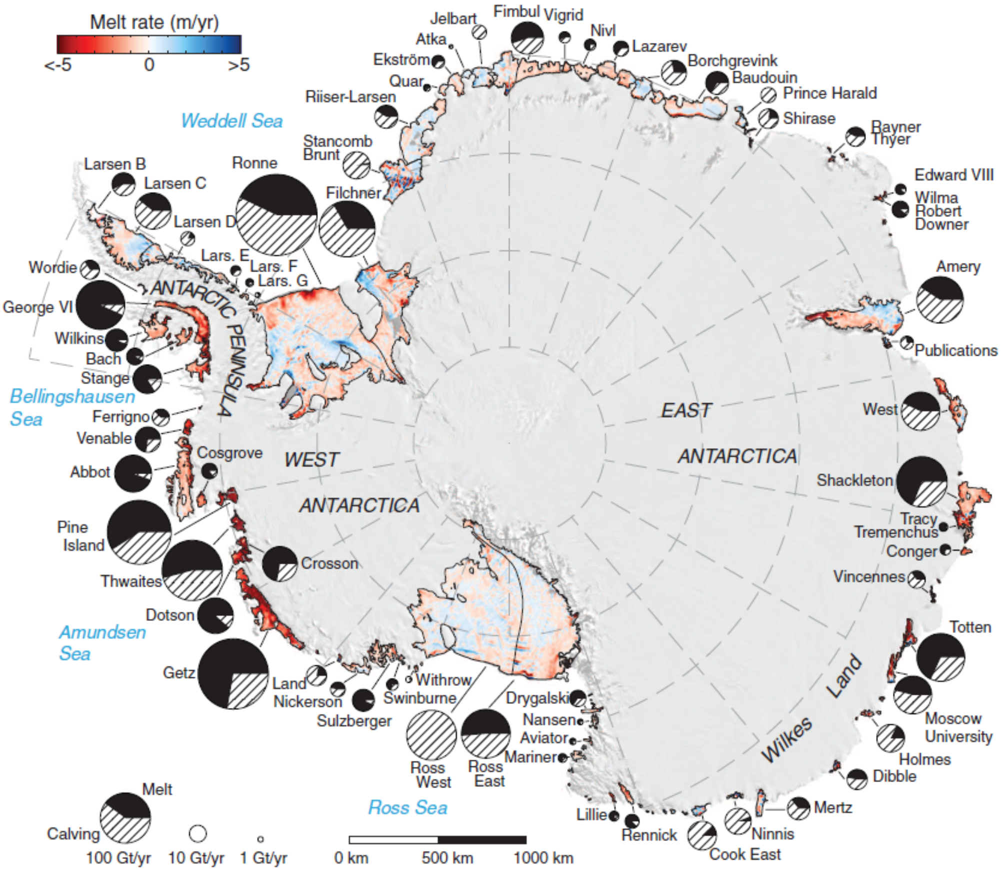


Figure 11: Basal melt rates of Antarctic ice shelves color coded from < –5 m/year to > +5 m/year (red areas indicate melting, blue areas indicate freezing) overlaid on a 2009 Moderate Resolution Imaging Spectroradiometer (MODIS) mosaic of Antarctica. Ice-shelf perimeters in 2007–2008, excluding ice rises and ice islands, are thin black lines. Each circle graph is proportional in area to the mass loss from each shelf, in GT/year, partitioned between iceberg calving (hatch fill) and basal melting (black fill). (Rignot et al., 2013). See Table 1 and Table S1 in Rignot et al., 2013 for additional details on ice shelf locations, areas, and mass balance components.

Ice-ocean interaction influences the stability of Antarctic ice sheets and ice shelves (floating extensions of the grounded ice sheet) through several critical processes. Warming ocean temperatures or changes in circulation can bring warm ocean water in contact with ice shelves increasing melt rates. This is particularly important in Antarctica where surface melt rates at the ice-air interface are typically low (Joughin *et al*., 2012). At the Antarctic ice shelf-ocean interface, surface waters are typically cold and fresh and near the surface freezing point resulting in relatively modest melt rates (although tidal motions and ocean currents can drive significant melt even in cases where the temperature difference between ice and ocean is small, e.g. Joughin and Padman (2003)). In contrast, at some locations around Antarctica, warm CDW comes into contact with glacial ice at depth causing larger melt rates. Where CDW or modified CDW reaches the ice at depth, the temperature difference driving basal melt is enhanced due to the pressure-dependence of the freezing point of sea water (Joughin *et al*., 2012). Bathymetric troughs on the continental shelf are key regions that act to channel the warm water towards the floating glaciers (Walker et al, 2007; Wåhlin et al, 2013). Conversely, shallow bathymetry can restrict the access of ocean heat to the sub-ice shelf cavity (e.g. Jenkins et al., 2010; Jacobs et al., 2011). Ocean currents can also aid in the calving of ice shelves by transporting icebergs away from the calving site, keeping ice moving through the area and speeding up the calving rate, while shallow banks and sills can act as pinning points for icebergs and ice tongues and may slow the rate of calving.

Ice shelf cavities are categorised as “warm” or “cold”. In the former, relatively warm CDW originating from the Antarctic Circumpolar Current intrudes onto the continental shelf and reaches the ice shelf (Figure 12). This water is well above the local surface freezing point and can enhance basal melt rates by tens of metres per year or more (Joughin *et al*., 2012). “Cold” cavity ice shelves are largely isolated from contact with warm CDW. Melting in cold as well as warm cavities is influenced e.g. by tidal mixing (Robertson, 2013) . Brine rejection during sea ice formation produces a dense, relatively saline water mass known as High Salinity Shelf Water (HSSW). The temperature of HSSW is at the surface freezing point. Circulation of HSSW beneath ice shelves can drive high melt rates at deep grounding lines due to the effect of pressure on the local melting point (Jacobs et al., 1992; Joughin *et al*., 2012). The larger cold-cavity ice shelves (Ross, Filchner and Ronne) account for only 15% of net melt, whereas ten southeast Pacific ice shelves and six warm-cavity East Antarctic ice shelves have high melt/area ratios, suggesting large ocean heat flux at their grounding lines (Rignot *et al.*, 2013). Recent modelling suggests that the Filchner-Ronne ice shelf could switch from a cold cavity to a warm cavity ice shelf as a result of a re-direction of relatively warm coastal currents caused by changes in wind forcing (Hellmer *et al*., 2012). This example illustrates how changes in ocean temperature, circulation or both can alter the supply of heat driving basal melt of ice shelves and floating glacier tongues.

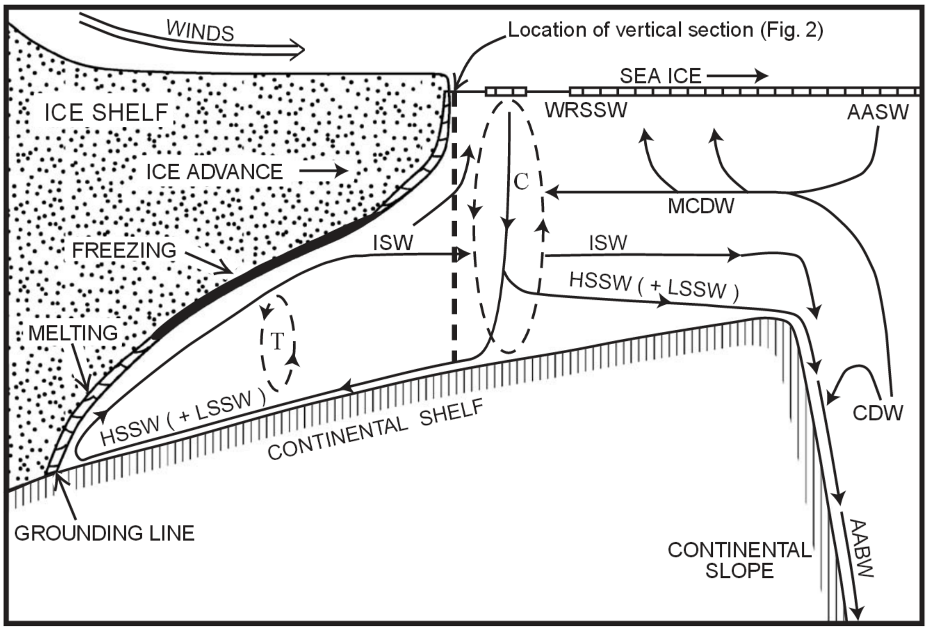


Figure 12: Schematic diagram of ocean – ice shelf interaction: circulation and water mass formation in a vertical plane perpendicular to the Ross Ice Shelf front. AASW = Antarctic Surface Water, CDW = Circumpolar Deep Water, MCDW = modified CDW, WRSSW = Western Ross Sea Surface Water, ISW = Ice Shelf Water, HSSW = high salinity shelf water, LSSW = low salinity shelf water, AABW = Antarctic Bottom Water. Winter convective missing is designated by the dashed circulation cell labeled C and tidal mixing is designated by the dashed circulation cell labeled T. (Smethie and Jacobs, 2005).

Recent modeling suggests that collapse of the Thwaites Glacier through melt-induced thinning may have already begun, with the onset of rapid collapse (>1mm per year of sea level rise) possibly closer to a few centuries than a millennium (Joughin *et al*. 2014). The Pine Island Glacier grounding line lies well below sea level and over bedrock that deepens inland, lending it susceptible to the marine ice sheet instability mechanism. Thinning of the glacier since the 1980s has been attributed to enhanced basal melt of its ice shelf by ocean heat flux (Pritchard et al., 2012) resulting from a change in sub-ice shelf circulation (Jacobs et al., 2011). The grounding line has retreated tens of kilometers since 1992 and there appear to be few grounded pinning points to stabilize the retreat (Rignot et al., 2014). Models suggest continued retreat of the Pine Island Glacier in the future that may contribute 3.5-10 mm of eustatic sea level rise over the next 20 years (Favier *et al.*, 2014). If the entire marine-based West Antarctic Ice Sheet (WAIS) were to collapse, it would contribute 3.3 m to global sea level-rise (Bamber *et al.,* 2009).

Airborne geophysical measurements have revealed that, like the WAIS, large parts of the East Antarctic Ice Sheet (EAIS) are also marine-based, with bedrock that deepens inland, and hence are potentially subject to the marine ice shelf instability. In particular, recent work using the new data have shown that the Wilkes and Aurora Sub-glacial Basins (WSB and

ASB), two of the largest reservoirs of sea level potential on the continent, are broader, deeper, and more susceptible to marine ice sheet instability than previously understood (Fretwell et al., 2013). The recent unveiling of the broad morphology, coastal connections, and paleo-fjords in the ASB, combined with paleoclimate evidence that East Antarctica may have made a substantial contribution to sea level rise in past warmer climates (Miller et al., 2012) indicate a dynamic early ice sheet with a significant erosional history and multiple ice sheet configurations (Young et al., 2011; Roberts et al., 2011).

The Totten Glacier drains nearly 7 meters of eustatic sea level potential from the ASB into the Sabrina Coast while recent thinning signals (Flament and Rémy, 2012; McMillan et al., 2014) and regional mass loss estimates occurring along the coast are the largest in Antarctica after only the Pine Island and Thwaites Glaciers in West Antarctica, and the mass loss has recently accelerated (Chen et al., 2009). The character of the thinning suggests that it may be caused by enhanced basal melting due to ocean processes (Pritchard et la., 2012). However, establishing whether these changes are due to ice dynamics, a delayed response to earlier climate forcing, or enhanced ocean forcing will require direct oceanographic observations.

Warming atmospheric temperatures and surface melt have resulted in large-scale ice shelf collapse in the Antarctic Peninsula, leading to a reduced buttressing effect and enhanced glacier flow. Ice shelves in the Amundsen Sea coast have stayed largely intact but the ice flow has accelerated. In this region, high rates of thinning (up to 10 m per year) are proposed to gradually reduce buttressing and initiate feedbacks (further thinning and grounding line retreat) that act to enhance ice loss (Joughin *et al*., 2012). Accelerated ice flow may increase rifting and crevassing, further destabilizing the ice shelves, and as the grounding line retreats further (in the case of bedrock sloping downward to the interior) more ice is exposed to warmer ocean waters.

The susceptibility of the Antarctic Ice Sheet to ocean heat transport remains poorly known; in large part due to the lack of ocean observations. Hydrographic data and moored time series are sparse over the continental shelf, especially in winter. Winter data are almost exclusively limited to seal data from particular regions. Observations in the sub-ice shelf cavity itself are limited to measurements obtained through several boreholes (e.g. in the Ross, Filchner-Ronne and Amery ice shelves, Jacobs et al., 1979; Nicholls and Jenkins, 1993; Allison 2003) and several unmanned submarine transects beneath the Pine Island Glacier (Figures 13 and 14; Jenkins et al., 2010; Jacobs et al., 2011). There is a need to measure both temperature and circulation, as both can contribute to changes in ocean heat flux to the base of floating ice shelves (e.g. Hellmer et al., 2012). Variability in atmospheric forcing, with both local and remote origins, can drive variability in basal melt rates by altering the temperature structure and circulation in the vicinity of the ice shelf (Jacobs *et al.*, 2013; Dutrieux *et al*. 2014).

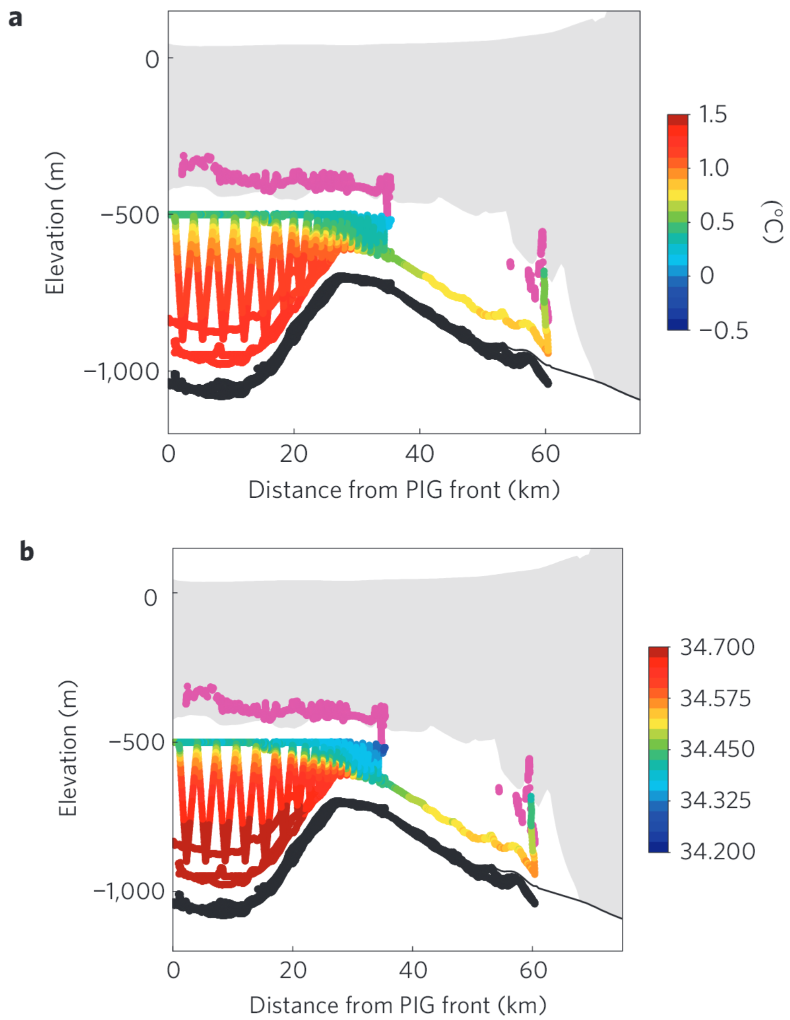


Figure 13: Seawater properties observed in the ocean cavity beneath the PIG ice shelf. Potential temperature (°C) (a), salinity (b), as measured by Autosub. (Jenkins et al., 2010).

Several physical or dynamical barriers act to limit the transport of ocean heat from offshore to the grounding line: the Antarctic Slope Front, the shelf break, the continental shelf, the ice front, the boundary layer beneath the ice shelf, and bathymetry in the ice shelf cavity. Observations are needed to provide insight into the processes that allow these barriers to be crossed. The circulation on the continental shelf is strongly influenced by bathymetry, which is poorly known over much of the Antarctic continental shelf and beneath ice shelves. High resolution bathymetric data sets now exist for some regions, like the Ross and Amundsen Seas, but much more data is needed. More work is also required to better understand the processes and quantify the rates of grounding line migration and iceberg calving.

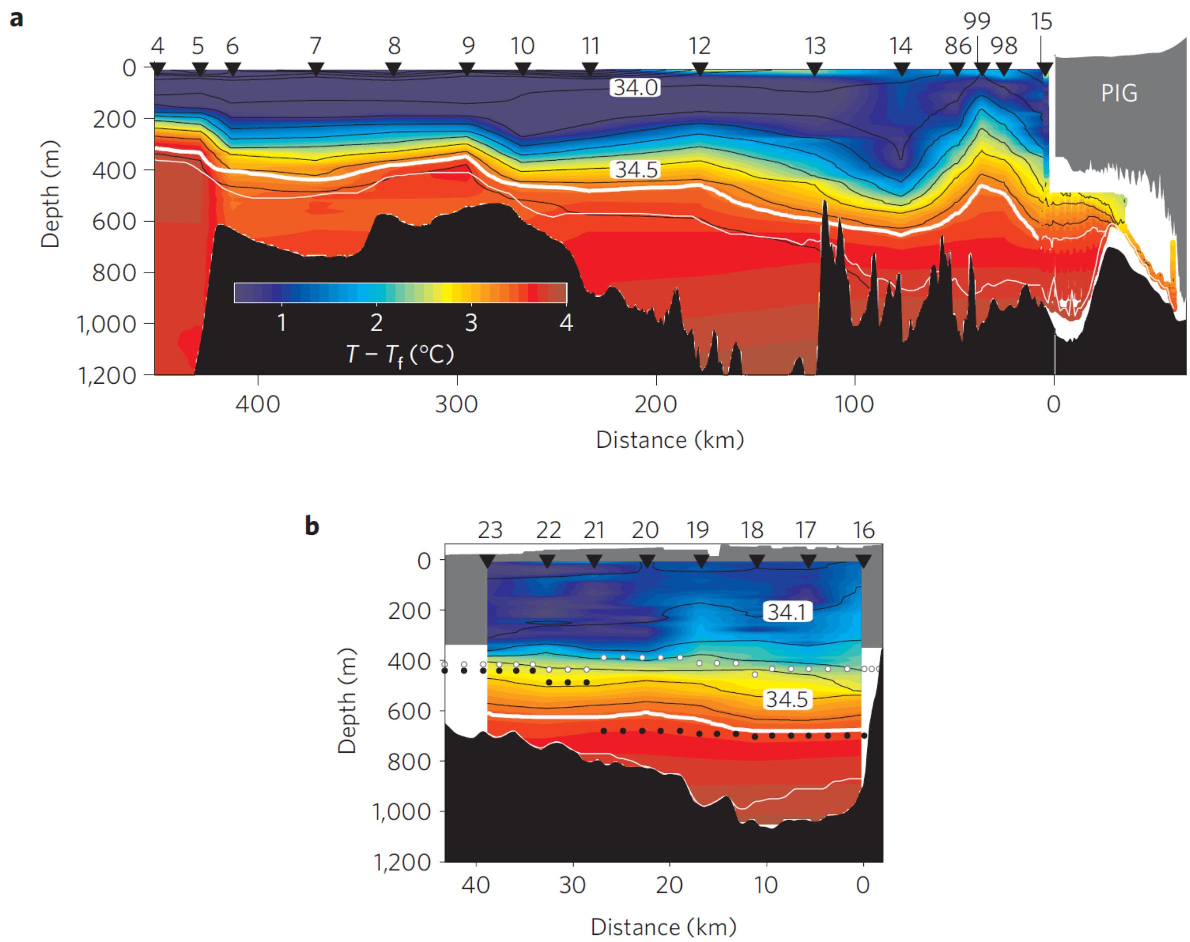


Figure 14: Vertical temperature and salinity sections. ***a,b****, Vertical temperature and salinity sections (****a****) across the continental shelf and beneath the Pine Island Glaceri (PIG) and (****b****) along the PIG calving front, looking toward the ice shelf. Both panels show temperature in colour relative to the in situ freezing point, salinity by black contours and the surface-referenced 27.75 isopycnal and potential temperature maximum by thick and thin white lines. Open circles in* ***b*** *show ice draft above the ridge crest (black dots) beneath the PIG, from airborne radar and Autosub measurements. (Jacobs et al., 2011).*

Sea ice also influences ocean – ice shelf interaction. The most direct mechanism is through the production of HSSW by brine rejection during sea ice formation. Dense HSSW can circulate beneath the ice shelf to the grounding line, where it can drive high melt rates due to the pressure dependence of the freezing point of sea water. Polynyas can remove substantial amounts of heat from the ocean over the continental shelf, reducing the heat available for melting of ice shelves (Khazendar et al., 2013; Gwyther *et al.,* 2014). Land-fast sea ice can help stabilise ice shelves and floating glacier tongues (Massom *et al.,* 2010) and pack ice can damp surface waves that contribute to erosion of ice fronts. In turn, input of glacial melt water can influence sea ice formation by changing ocean stratification (e.g. Bintanja et al., 2013).

3. OBJECTIVES AND KEY SCIENTIFIC QUESTIONS

The background provided in Section 2 provides the scientific motivation for the development of an under-ice component of the Southern Ocean Observing System. To guide the design and implementation of the observing system, the workshop identified overall objectives and key scientific questions within each theme. Several of these were highlighted by the SCAR Horizon Scan in its assessment of the most pressing issues for Antarctic and Southern Ocean science over the next 20 years (Kennicutt et al., 2014). The observing system and resources needed to address these questions is discussed in Section 4.

3.1 Circulation and inventories of heat, freshwater and carbon in the sea ice zone

Objectives:

1. To quantify how much heat, freshwater and carbon are stored by the ocean between the winter sea ice edge and the Antarctic continent.
2. To understand the processes responsible for ocean storage of heat, freshwater and carbon and their sensitivity to changes in forcing.

Key Scientific Questions:

1. What is the time-evolving inventory of ocean heat and freshwater content between the winter sea ice edge and the Antarctic continent?
2. What is the time-evolving inventory of natural and anthropogenic carbon between the winter sea ice edge and the Antarctic continent?
3. How do Antarctic and Southern Ocean processes influence the distribution of thermosteric sea level rise?
4. How much heat, freshwater and momentum is exchanged between the ocean and atmosphere in the sea ice zone and how do air-sea fluxes vary in space and time?
5. What are the key physical processes regulating exchange between the open ocean and the continental shelf?
6. What processes set the stratification of the upper ocean and its response to changes in forcing?
7. What is the residence time of continental shelf waters and how does it vary around the Antarctic continent?
8. What are the relative contributions of air-sea fluxes, sea ice formation and melt, and mixing in driving water mass transformations in the sea ice zone?
9. What is the strength of the overturning circulation in the sea ice zone and how and why does it vary in time and space?
10. Where, how and in what quantity, is Antarctic Bottom Water formed?
11. What is the contribution of tidal motions to cross-shelf exchange, bottom water formation and export, and diapycnal mixing?
12. What is the transport of the sub-polar gyres and boundary currents (e.g. Antarctic Slope Front, deep boundary currents) in the sea ice zone?

13. How does the circulation in the sea ice zone respond to modes of climate variability and to long-term trends associated with anthropogenic forcing (e.g. ozone and greenhouse gases)?
14. How strong is diapycnal and isopycnal mixing in the sea ice zone, where does it occur, what physical mechanisms are responsible for mixing, and how important is mixing to horizontal and vertical transport?
15. What are the dynamical barriers to transport between the open ocean and the continental shelf (e.g. on-shelf flow of Circumpolar Deep Water and export of dense shelf water) and where are these barriers breached?
16. How important are canyons, troughs and ridges on the continental shelf and slope to meridional transport?
17. What are the contributions of precipitation, sea ice formation and melt, iceberg calving and melt, basal melt, and glacial run-off to the freshwater balance?
18. How would the ocean circulation respond to a large influx of glacial melt water resulting from ice shelf collapse and rapid retreat of Antarctic glacial streams?
19. To what extent are changes in the Antarctic Circumpolar Current (e.g. a southward shift) or change in the overturning circulation (e.g. change in upwelling) linked to changes in heat transport across the continental shelf?
20. What drives changes in the ocean thermocline (hence heat input) near the Antarctic continental shelf break?

3.2 Ocean – sea ice interaction

Objectives:

1. To determine the processes controlling the circumpolar and regional distribution of sea ice concentration and sea ice thickness.
2. To determine how and why the concentration and thickness of Antarctic sea ice varies over time-scales from days to millennia.
3. To understand and quantify coupled interactions between Antarctic sea ice, the ocean, the atmosphere, and ice shelves.

Key Scientific Questions:

1. What is the circumpolar and regional distribution of Antarctic sea ice and how does it vary in time?
2. What is the contribution of snow ice to the overall mass of Antarctic sea ice?
3. How do waves influence the growth and disintegration of sea ice?
4. How does the sea ice drift and convergence or divergence vary with space and time around Antarctica?
5. What is the air-sea flux of momentum, heat and freshwater in the sea ice zone (including in closed pack, leads and polynyas)?
6. How does the presence of sea ice influence the dynamics of Antarctic ice shelves and glacier tongues?

7. How does glacial melt water affect the dynamics of Antarctic sea ice?
8. What ocean-ice feedbacks are involved in the advance and retreat of sea ice?
9. What is the contribution of ice shelf water and platelet ice to formation of sea ice?
10. What is the regional and circumpolar distribution of fast ice around Antarctica, how does it vary in time, and how does fast ice influence pack ice and ocean circulation?
11. What is the contribution of sea ice formation and melt to water mass formation?
12. How do changes in sea ice thickness, concentration and seasonality affect atmospheric circulation? Are there significant feedbacks between sea ice and atmosphere?
13. How do teleconnections between low and high latitudes influence Antarctic sea ice?

3.3 Ocean – ice shelf interaction

Objectives:

1. To determine the sensitivity of Antarctic ice shelves to changes in ocean circulation and temperature.
2. To assess the effect of basal melt of floating ice shelves on the mass balance of the Antarctic ice sheet and its contribution to sea level rise.
3. To determine the response of the ocean to changes in the freshwater input by the Antarctic ice sheet.

Key Scientific Questions:

1. What controls the rate at which ocean heat is transferred through the various barriers regulating heat transfer from ocean to ice shelf, including exchange across the continental shelf break, transport across the continental shelf, inflow to the ice shelf cavity, and delivery to the ice shelf base and grounding line?
2. How sensitive is the rate of basal melt to changes in large-scale climate forcing (e.g. winds, air-sea heat exchange, and sea ice formation and melt), including teleconnections to lower latitudes?
3. Why do some ice shelves in East Antarctica experience high ratios of basal melt to iceberg calving, despite being further removed from warm ocean waters than those in the Amundsen/Bellingshausen Seas?
4. What are the relative contributions of oceanographic and glacial dynamics to thinning of Antarctic glacial streams?
5. How does polynya activity influence the rate of basal melt and vice versa?
6. What are the relative contributions of melt at the grounding line, melt (and refreezing) at the base of the ice shelf, and melt at the ice front, to the net basal melt?
7. What controls the rate of iceberg calving?
8. What is the magnitude and spatial distribution of freshwater input by melting icebergs?
9. What is the shape of the ice shelf cavities (i.e. sea floor bathymetry and basal topography of floating ice) and how does this influence the circulation beneath ice shelves?

10. How important are tides for transferring ocean heat to the base of floating ice shelves and glacier tongues?
11. How sensitive is the mass balance of the Antarctic ice sheet, and therefore sea level rise, to ocean-driven thinning and/or disintegration of floating ice shelves?
12. What ocean observations are currently the most important for ground-truthing satellite-based and numerical modeling estimates of ice shelf mass balance?

4. An Integrated Under-ice Observing Strategy

A sampling strategy for an integrated under-ice observing system is outlined in this section. The under-ice observing system requires a mix of observations: sustained measurements and focused process studies, from in situ and remote sensing instruments, covering the ocean, atmosphere, and cryosphere, and including year-round sampling from the ocean surface to the sea floor, and from the winter ice edge to the Antarctic coastline or grounding line. This is a huge challenge. The strategy outlined here takes advantage of recent technological developments and experience in the Arctic, where implementation of an observing system is more advanced. We also discuss the potential role of instrumentation that is in development but not yet available.

The Antarctic sea ice zone includes several distinct physical environments (Figure 15). The sampling needs and technologies available for measuring each environment are different. We therefore discuss the sampling strategy by considering each domain in turn.

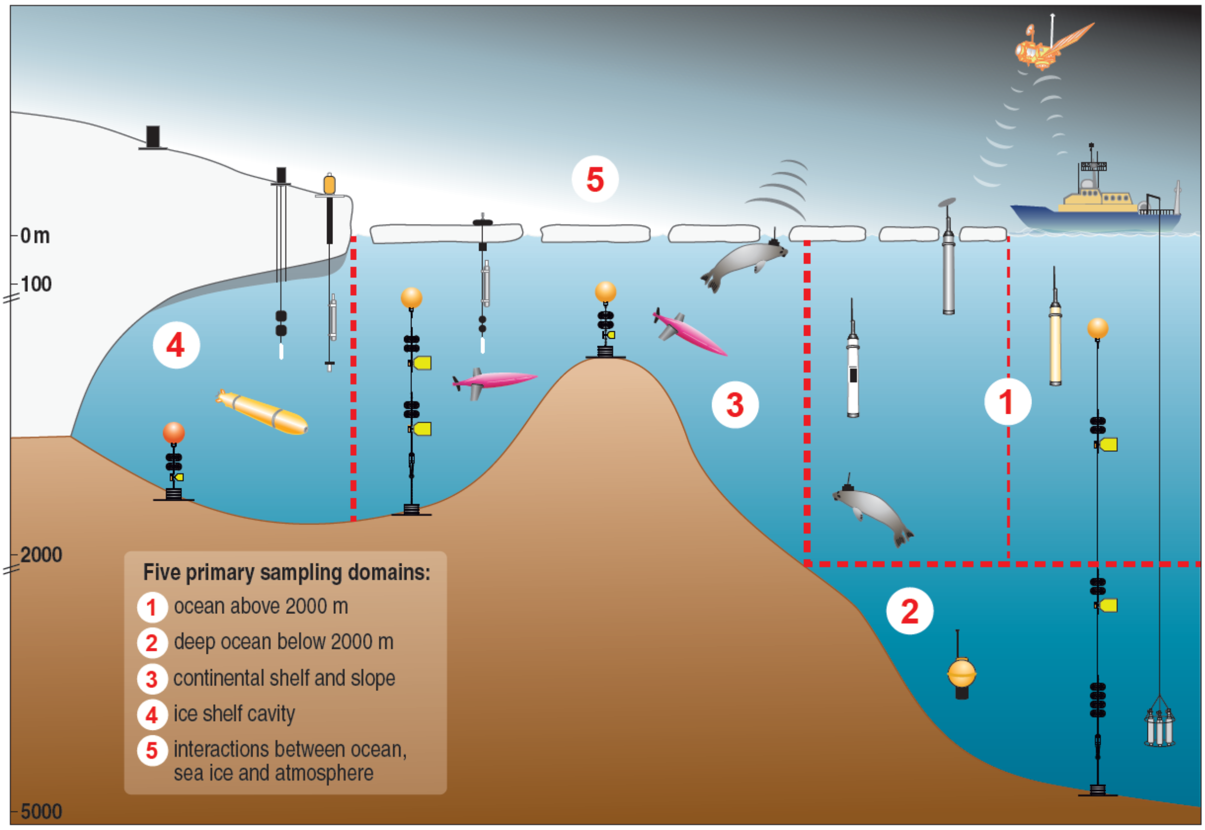


Figure 15: The high latitude Southern Ocean and Antarctic margin includes several physical environments, each with distinct characteristics that mean a different mix of platforms is appropriate in each case. See the Tables below for a summary and explanation of the observing strategy in each domain..

Open ocean shallower than 2000 m depth

Many of the key science questions require broad-scale measurements of the evolving inventory of temperature and salinity in the ocean. Observations of velocity and transport on broad-scales are also needed, either by direct measurement (e.g. by current meter moorings, float drift, or ship-based acoustic Doppler current profiler (ADCP)) or inferred from geostrophy or altimetry (Table 1).

The WOCE/CLIVAR repeat sections, coordinated by GO-SHIP, provide a starting point for sustained hydrographic observations in the open ocean region. The WOCE sections are sustainable but they need to be complemented by measurements that are more densely sampled in time and space. Argo floats now provide the back-bone of the global ocean observing system for temperature and salinity above 2000 m (Figure 16). Drift trajectories provide information on absolute velocity at the parking depth, usually 1000 m. Profiling floats adapted to operation in the sea ice zone will likely play a similar role in the under-ice observing system.

Ice-capable floats employing either ruggedized antennae or ice-avoidance algorithms have been successfully deployed in the high latitudes since the early 2000's. By avoiding coming to the surface when surface waters are sufficiently cold that ice might be present, these floats collect and store profiles through the winter. The drawback is the lack of position data for each profile, as the float is required to surface in order to achieve a GPS fix through the satellite network. For slow drifts, interpolation between surface fixes may have errors less than 20km (Riser, pers. comm..), which may be sufficient for many applications, particularly when a sufficient number of floats are deployed in an area.

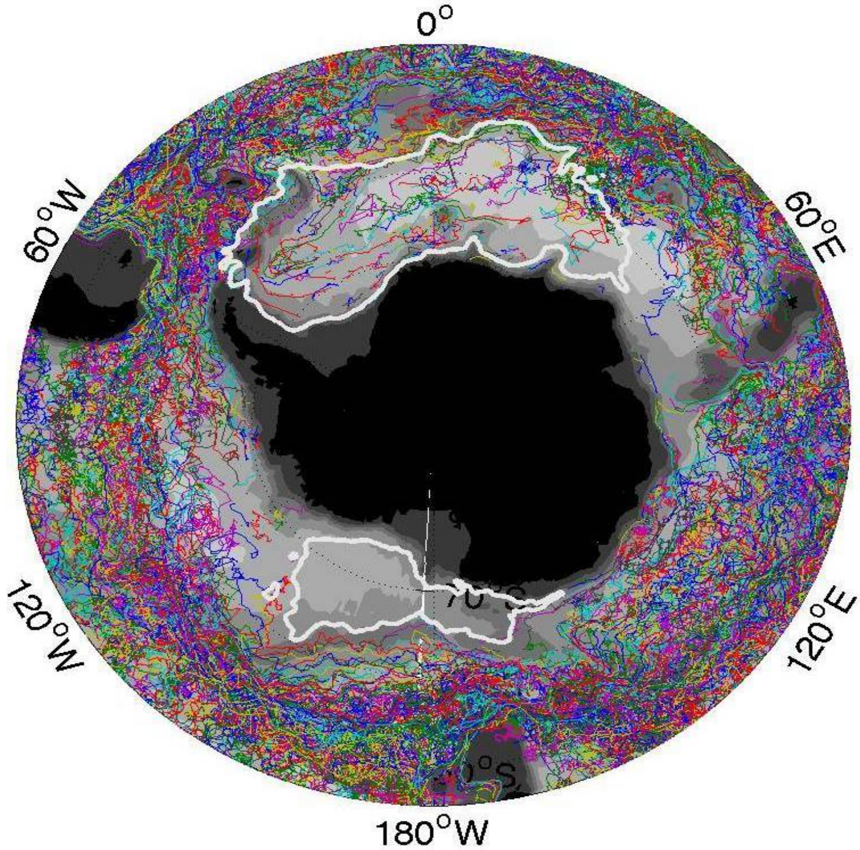


Figure 16: Argo float trajectories. Note the large voids in the sea ice zone (partially filled in the Weddell Sea by acoustically-tracked profiling floats).

Acoustic tracking of floats through an array of moored sound sources, as done now in the Weddell Sea, allows accurate positioning of each profile, but at increased cost (Figure 17). Acoustic conditions under Antarctic sea ice can be challenging, limiting effective range and accuracy of acoustic navigation. Improvements in technology (e.g. sound sources, receiver technology and signal processing) are needed. The under-ice observing system will use acoustic tracking in regions where acoustic tracking is cost-effective (e.g. in the major gyres such as the Ross and Weddell Seas where floats are retained) and rely on floats with ice-avoidance algorithms or ruggedized antennas in the remainder of the sea ice zone. New approaches to float navigation (e.g. use of earth's magnetic field and bathymetry, GPS through ice, and 3-axis digital magnetometer) are also being explored.

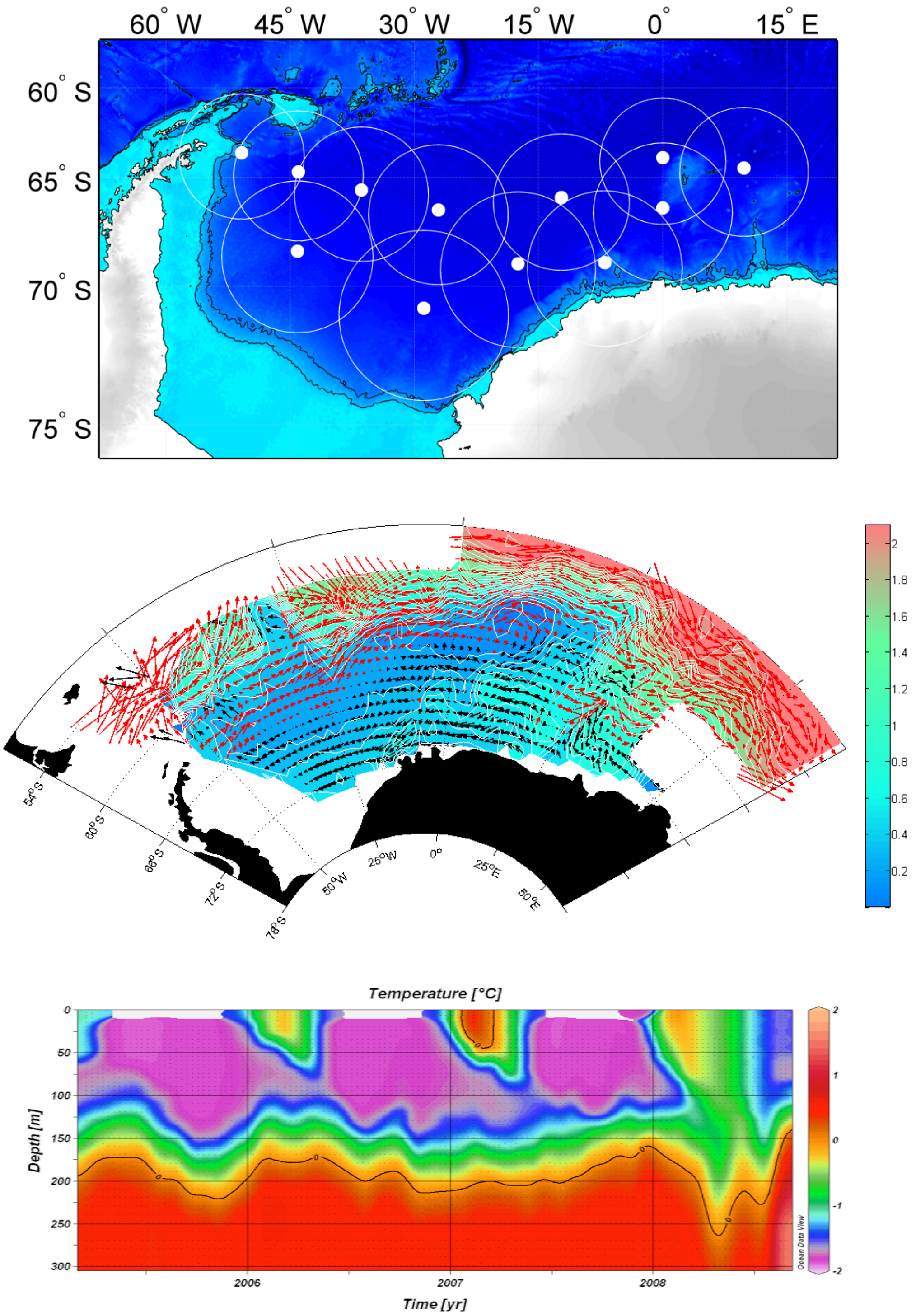


Figure 17: Location of acoustic sound sources in the Weddell Sea (top). Temperature and velocity in the Weddell Sea, derived from 5633 float profiles (note that the WOCE CTD data base includes 800 casts in this region) (middle). The floats provide year-round data, including under the sea ice (bottom, sea ice indicated in white) (O. Boebbels, AWI).

Oceanographic sensors attached to seals and other Antarctic animals (e.g. whales and penguins) to study their behavior and biology will contribute to the goal of broad-scale sampling of temperature and salinity in the sea ice zone (Figure 18). Instrumented animals have now provided around 70% of all oceanographic profiles south of 60˚S in the World Ocean Data Base (Fedak, 2013). This contrast is even more dramatic if winter profiles are considered (as seals are most actively foraging deep in the sea ice pack and capturing data over the winter/early spring months). Seals also sample parts of the continental shelf, where profiling floats typically do not currently sample. The distinct sampling characteristics of data from floats and seals make these platforms complementary. However, the current accuracy of sensors placed on seals is lower (temperature ± 0.05˚C and salinity ± 0.05; Roquet et al., 2013) than that of Argo floats (temperature ± 0.002˚C and salinity ± 0.01).

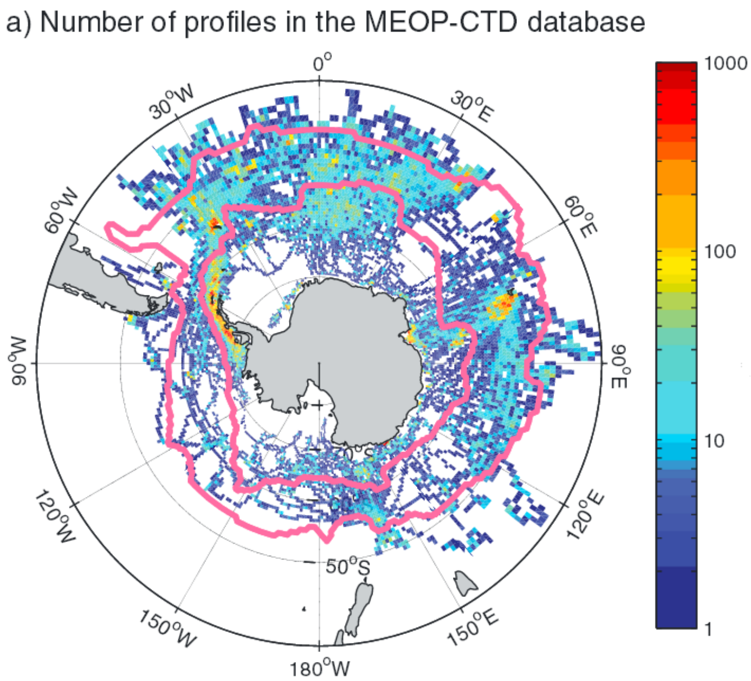


Figure 18: Location of oceanographic profiles collected by instrumented seals (number of temperature and salinity profiles per ECCO grid cell for the MEOP-CTD database), from Roquet et al., 2013).

Repeat hydrographic sections are another key platform in the under-ice observing system (Figure 19). Ship-based hydrographic transects are the only way to sample the full-depth of the ocean for a wide range of physical, biogeochemical and biological variables. Tracers of particular relevance to the under-ice observing system include carbon (to quantify changes in inventory of natural and anthropogenic carbon dioxide), oxygen and CFCs (as measures of ventilation), isotopes and trace gases (as measures of ice melt, both sea ice and glacial ice), and trace elements like iron (to quantify the supply of micro-nutrients). Ship-mounted and -lowered ADCP data collected on these lines help quantify the absolute velocity field. The GO-SHIP repeat hydrographic sections (Figure 19) that cross the sea ice zone should be repeated every 5-7 years at a minimum (see GO-SHIP requirements). It is important that the southern ends of these sections are occupied with ice-capable ships to ensure the sections cross the continental slope and shelf.

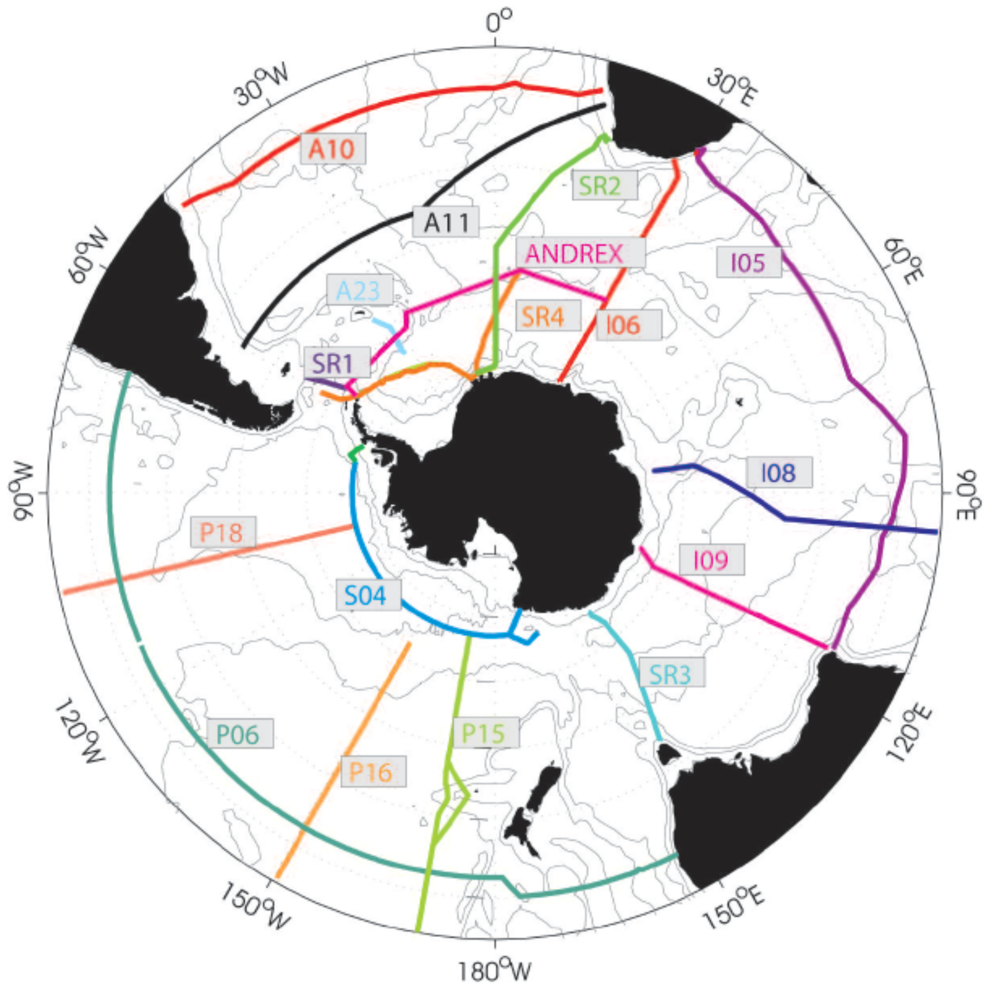


Figure 19: Location of repeat hydrographic sections contributing to the Southern Ocean Observing System (SOOS) and GO-SHIP (from Rintoul et al., 2012).

In addition to the GO-SHIP lines, it would be of great value to establish a set of additional zonal and meridional hydrographic lines in the sea ice zone, for example as carried out during the SASSI program of the IPY (Figure 20). Sections near Antarctic bases would be most feasible in terms of logistics. These sections could be occupied as part of resupply voyages and by nations that lack the resources to carry out trans-basin, full-depth repeat hydrography.

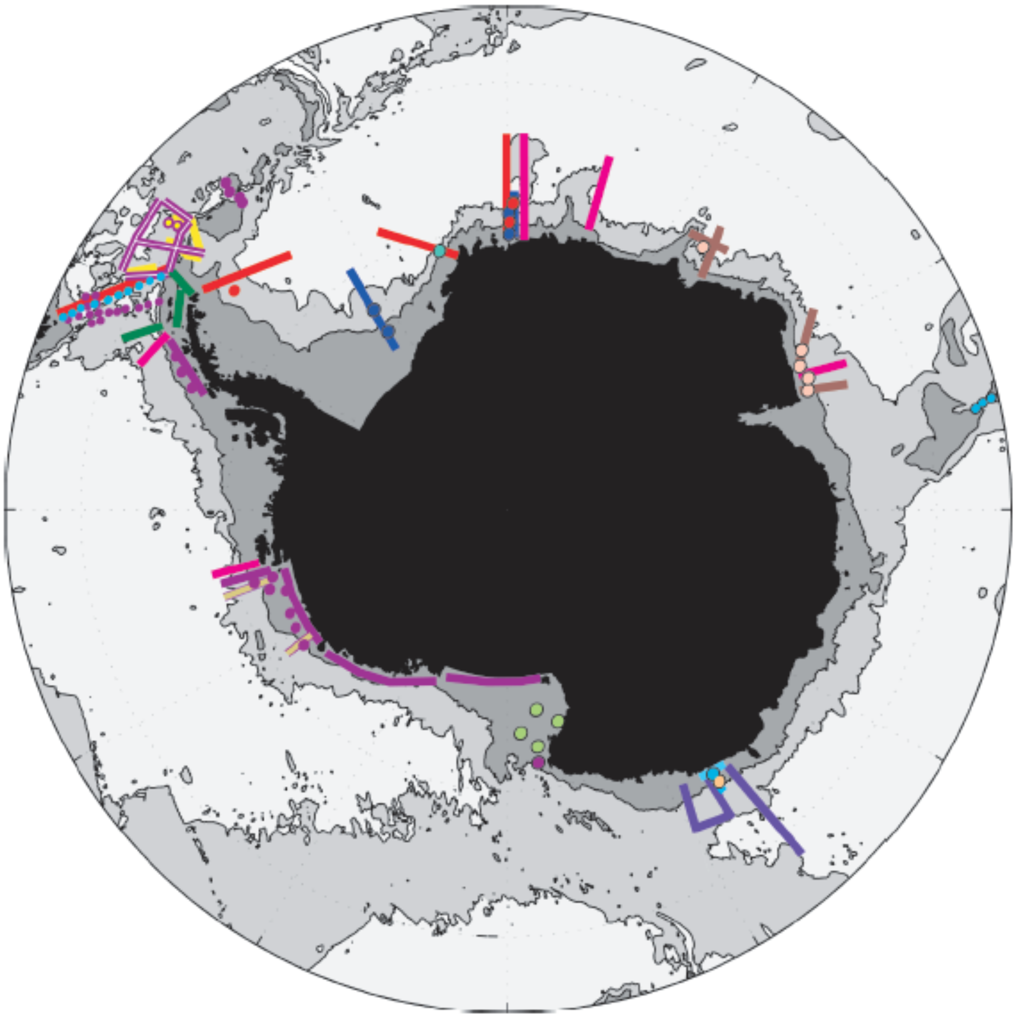


Figure 20: Location of hydrographic sections (lines) and moorings (circles) occupied during the SASSI program of the International Polar Year. Sustained occupations of these sections and arrays would make a substantial contribution to an under-ice observing system. From Rintoul et al., 2012.

The ice-covered ocean has traditionally been out of reach of satellite altimetry. New approaches have been developed in the Arctic to determine sea surface height and ocean circulation (Giles et al., 2011) that may be appropriate for the Antarctic sea ice zone.

Table 1: Platforms contributing to sustained broad-scale measurements of the upper 2000 m of the ocean in the sea ice zone.

Platform	Sampling requirements
Ice-capable Argo in water depths greater than 2000 m	Minimum requirement is consistency with global Argo design of 1 profile per 3 x 3° square every 10 days. This requires maintaining a minimum array of 320 active floats south of 60˚S. Increased failure rate (20%) of ice floats needs to be taken into account through regular deployments. If floats are deployed from

	a research vessel, a CTD should be conducted with each float deployment wherever possible for calibration purposes. Measure P, T, S and O_2 from the surface to 2000 m in open water and from the ice-ocean interface to 2000m in ice-covered seas.
Acoustically-tracked Argo in Weddell and Ross gyres	Maintain the current array of ~11 active sound sources and ~80 RAFOS-equipped floats in the Weddell gyre. A similar array of sound sources and ~110 acoustically tracked floats are needed in the Ross Gyre. Development of new low frequency sound sources with greater coverage may allow the number of sound sources to be halved. Measure P, T, S and O_2 from the surface to 2000 m in open water and from the ice-ocean interface to 2000m in ice-covered seas.
Seal tagging	Maintain or enhance Marine Mammals Exploring the Oceans Pole to Pole (MEOP) sampling. CTD-satellite relay data loggers deployed on Weddell and Southern elephant seals in the Southern Ocean and sub-Antarctic islands. Measure time, depth, temperature, conductivity, oxygen content, wet or dry status to maximum seal dive depth.
Hydrographic sections	Occupy GO-SHIP full-depth repeat hydrography lines at decadal and high-frequency intervals (see Hood, 2009). Add additional short meridional transects crossing the Antarctic slope and shelf where feasible (e.g. near Antarctic bases). Underway CTDs deployed on transit legs could expand sampling of the upper 1000 m of the water column. Measure P, T, S and O_2 at 2db resolution from the surface to sea-floor. Other core variables; phosphate, silicate, nitrate and nitrite, DIC, alkalinity, pCO_2 and pH and shipboard and lowered Acoustic Doppler Current Profiler (ADCP) measurements. Recommended variables: organic carbon (particulate organic carbon (POC), dissolved organic carbon (DOC) and underway surface measurements. Carbon isotopes (^{13}C, ^{14}C), chlorofluorocarbon tracers (CFC-11/12, SF_6), tritium and helium-3 should be measured on key sections (see Hood, 2009).
Satellite altimetry	Maintain JASON sampling; validate use of altimeter for determination of ocean circulation and sea level height in ice-covered seas in Antarctica

Deep ocean

Observations reveal rapid changes underway in the deep ocean, with the largest changes found in waters of Antarctic origin, but the drivers of the changes remain uncertain. Sustained observations of the deep water column in the sea ice zone are required. Most of the evidence for change in the deep ocean has been provided by repeat deep hydrography. Hydrographic sections are also the primary source of information on change in biogeochemical and biological variables (see above). Continued occupation of the GO-SHIP repeat hydrography lines is essential. These sections must measure the full-depth of the ocean, with complete tracers. The sections must be occupied with ice-capable vessels to ensure coverage of the continental shelf and slope at the southern end.

Hydrographic sections, while critical, are generally not occupied with sufficient frequency to resolve variability on time-scales shorter than decades. The repeat lines are also widely-spaced, with typically only a few lines per deep ocean basin. To understand the dynamics of the abyssal circulation and its sensitivity to changes in forcing, more frequent sampling with higher spatial resolution is needed. Deep Argo floats, now under development, will allow broad-scale measurements of the deep ocean to be made in the future.

The abyssal circulation in the Antarctic sea ice zone is dominated by boundary currents that export AABW to the rest of the global ocean. The strongest signals of change in bottom water properties are found in the core of the boundary currents. Moored arrays across the major boundary current systems will make an important contribution to the under-ice observing system. Development of long-endurance or expendable moorings, with capacity for data telemetry, would increase the cost-effectiveness of moored instrumentation and allow more widespread deployments.

A combination of these three approaches– periodic repeat hydrography with full tracers, deep Argo to provide broad-scale sustained measurements of water properties, and moored arrays in key boundary currents – would provide the information needed to understand the response of the deep ocean to climate variability and change (Table 2).

Table 2: Platforms contributing to sustained measurements of the deep ocean in the sea ice zone.

Platform	Sampling requirements
Hydrographic sections	Occupy GO-SHIP full-depth repeat hydrography lines, with biogeochemistry and tracers. Sections must extend across the continental shelf and slope. Add additional short meridional transects crossing the Antarctic

	slope and shelf where feasible (e.g. near Antarctic bases). Measurements as per Table 1.
Deep Argo	Pilot deployments underway now. When proven, need broad-scale deployments to sample deep ocean. Measure P, T, S and O_2 from the surface to the bottom in open water, from ice-ocean interface to the bottom in ice-covered seas. Required float density not yet specified.
Moorings	Deployed in key locations, including dense overflows and boundary currents. Development of long endurance moorings with data telemetry is needed to lower costs and allow broader deployment. Measure T, S, O_2, velocity and pressure at regular depths (including the bottom).

Continental shelf and slope

For many of the key questions highlighted in Section 3, sustained measurements of water properties on the continental shelf are essential (Figure 21). Continental shelves act as the gateway between the ocean and the ice shelves. Warm, offshore waters intrude onto the continental shelf, interact with resident water masses and the base of the ice sheet, and are transformed into lighter or denser water masses before being exported offshore. While some parts of the Antarctic continental shelf have been sampled regularly for many years (e.g. the western Antarctic Peninsula), very few observations have been made over most of the continental shelf. As a result, even the mean distribution of temperature and salinity over the shelf is poorly known, and much less is known about variability of shelf waters. Comprehensive bathymetric mapping is a key observation that is required to understand the pathways for water moving on and off the shelf; including the channeling of warm water towards glaciers, the export of dense water masses off the slope and iceberg stranding. Sustained measurements of water properties, circulation, and exchange across the continental shelf break are needed. Air-sea fluxes over the continental shelf, including in coastal polynyas, are also poorly known and must be measured to improve understanding of water mass transformations over the shelf. Bottom sampling for proxy indicators of temperature and other variables over centennial time scales could help elucidate the history of warm water incursions onto the Antarctic continental shelves.

The under-ice observing system will rely on a combination of multibeam bathymetric mapping, seal-borne sensors, floats adapted for operation on the shelf, ship and glider transects, ice-tethered profilers, and moorings in key locations to sample the continental shelf (Figure 15, Table 3).

Instruments deployed from aircraft will also be used to sample areas of the continental shelf that are impossible or impractical for marine vessels to visit often enough to observe near-coastal processes relevant to ice-ocean exchange. This capability will become increasingly important as regional and circum-Antarctic circulation models improve and requirements are defined for regular geographic and temporal sampling for proper validation of model results.

Table 3: Platforms contributing to sustained measurements over the continental shelf and slope.

Platform	Sampling requirements
Ice-capable profiling floats, adapted for use on the shelf	Floats may ground between profiles to increase residence time or include active bottom-avoidance. Measure P, T, S and O_2 from the surface to the bottom in open water, from ice-ocean interface to the bottom in ice-covered regions.
Ice-tethered profilers with velocity	Most cost-effective in multi-year or fast ice given short lifetime of most Antarctic sea ice. Measure P, T, S, O_2 and velocity.
Seal tags	Maintain or enhance MEOP sampling. Coverage of the shelf optimised by deployments in Antarctica, including shelf-resident species (Weddell seals). Measurements as per Table 1.
Hydrographic sections	Only platform capable of collecting full suite of physical, biogeochemical and biological variables. Measurements as per Table 1.
Gliders	Only platform capable of frequent, high resolution transects on the shelf and slope. Measure T, S, O2, velocity from the surface or ice-ocean interface to the sea floor (other variables: microstructure, downwelling irradiance).
Moorings	Deployed in key locations (e.g. polynyas, dense overflows).

	Measurements as per Table 2.
Airborne deployable instruments	Airborne assets are available near almost every coast in Antarctica often near areas of the ocean that are either inaccessible to ships or impractical for long term monitoring due to heavy ice conditions. Aircraft equipped with appropriate deployable instruments stand to provide access to some of these areas beginning with traditional Airborne Expendable Bathythermographs (AXBTs) in the short-term and will expand to more capable instruments in the years ahead.
Ice-capable vessels	Ship-based measurements over the continental shelf require ice-capable vessels. In many nations, ship time on research ice breakers is becoming more difficult to obtain. Enhanced international collaboration and asset sharing may help.

Ice shelf cavities

The key observation for studies of ocean – ice shelf interaction is the ocean heat flux to the ice shelf. Therefore measurements of velocity and temperature are high priority, both at the ice front and within the ice shelf cavity. A number of other parameters would help constrain estimates of basal melt, including salinity, oxygen, oxygen-18, and tracers of ice shelf melt (e.g. helium and neon).

Measurements on the continental shelf discussed above will help quantify ocean heat transport from the open ocean, across the continental shelf, to the ice shelf cavity, as well as the export of ice shelf water (Figure 21). Repeat sampling along the ice front is needed to measure ocean heat flux to the cavity and its variation with time. The topography of the sea floor and the underside of the ice shelf strongly influence the flow within the ice shelf cavity but are poorly known for all ice shelves.

Airborne gravity informed by concurrent magnetics can be used to map the broad bathymetry beneath ice shelves and are made more accurate with even a limited number of tie points. Modern gravimeters flown on the slower aircraft found in Antarctica (DHC-6 Twin Otter and the BT-67 Basler, in particular) can resolve seafloor topography on the order of the first Rossby radius of deformation. Airborne ice sounding radar can be used to measure the thickness of ice shelves to accuracies between 1 and 20 meters depending on the basal crevasse environment. Together, these techniques can determine the first order sub-ice shelf water column thickness.

Advanced airborne radar sounding techniques can be used to detect subglacial water systems from centimeters to tens of meters or more across and how they interact with grounding zones of major ice shelf cavities. These data can be used to constrain the subglacial fresh water flux into these cavities such, providing improved freshwater budgets and critical input to cavity circulation models.

Phase sensitive radar deployed on the glacial ice can directly measure vertical displacements of the ice-shelf base (hence basal melt) and internal structure of the ice shelf.

All of the above observations are required to underpin and validate the continued development of high resolution, regional, and circumpolar, ocean-ice shelf coupled models (Table 4).

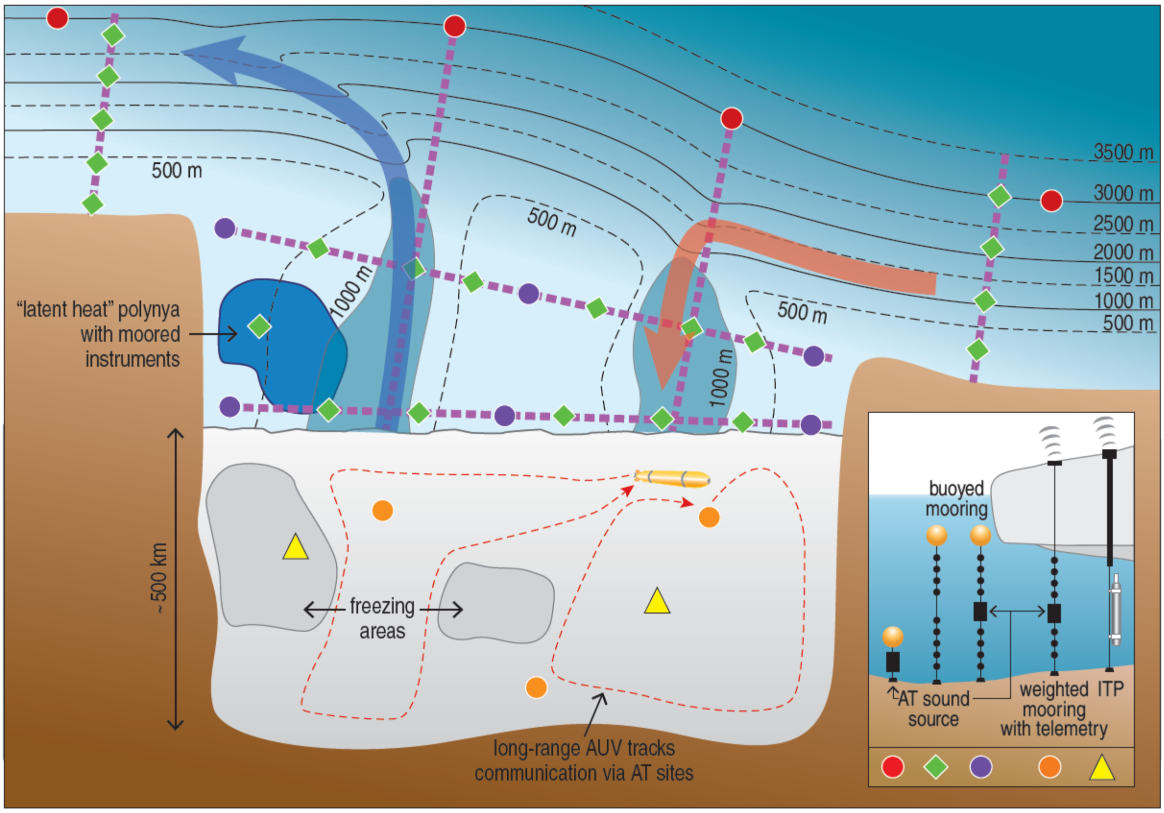


Figure 21: A strategy for observing ocean circulation, water properties and ocean-ice shelf interaction for a generic ice shelf configuration, including the continental shelf and slope and sub-ice shelf cavity. Symbols indicate different types of moored instrumentation, as shown in the inset. Acoustics will be used for navigation of autonomous vehicles, data telemetry and acoustic tomography. Large red and blue arrows indicate inflow and outflow from the ice shelf cavity, respectively. The dashed purple lines in the open ocean indicate CTD transects from ships and/or gliders. Thin dashed red lines indicate AUV tracks under the ice shelf.

Table 4: Platforms contributing to sustained ocean measurements in ice shelf cavities.

Platform	Sampling requirements
Unmanned submarines	Only proven technology to measure ocean properties along transectsin the sub-ice shelf cavity. New developments may allow extended missions. Key measurements for ocean – ice shelf interaction include T, S, velocity, oxygen, and swath mapping of sea floor and sub-ice shelf topography.
Sensors deployed through boreholes	Provide time series of sub-ice shelf properties and circulation and direct measurements of basal melt Both traditional oceanographic sensors and distributed temperature sensing (DTS) from fibre optic cables Exploit "boreholes of opportunity" drilled for other purposes such as geophysical research programs. T, S, O_2, velocity.
Hydrographic sections with tracers of ice shelf water	T, S, O_2. Oxygen-18, helium and neon can be used to track ice shelf water leaving the ice shelf cavity.
Moorings deployed by ROVs	Not yet a proven technology, but promises to allow a wider range of instrumentation to be deployed and recovered from the ice shelf cavity.
Ship and glider transects & moorings across the ice front	Needed to measure ocean heat flux to ice shelf cavity. Year-round sampling needed. May require acoustic navigation under sea ice (and under ice shelves)? T, S, O_2, velocity and tracers from ship transects.
Airborne Remote Sensing	Radar sounding is needed to determine the thickness of ice shelves and grounding zones and to infer the location and activity of subglacial water systems so that subglacial flux into ice shelf cavities may be constrained. Gravity and magnetics acquired on sufficiently slow aircraft (e.g. DHC-6, BT-67, helicopter) are needed to infer the sub-ice shelf seafloor shape on the order of the first Rossby radius of deformation.
Phase sensitive radar on ice shelves and glacier tongues	Provide direct measurements of basal melt.

Acoustic tomography	Potential to resolve time series of circulation and temperature within the full ice shelf cavity. Explore potential to use same acoustic sources for multiple purposes (navigation, tomography).

Sea ice

Progress in understanding the processes that control the mass, distribution and variability of Antarctic sea ice requires enhanced observations of sea ice and its interactions with the ocean and atmosphere. In particular, coincident accurate measurements of sea ice extent, concentration, thickness and drift are needed. Simultaneous measurements of changes in sea ice thickness, snowfall, ocean temperature, and surface meteorology over time are needed at a variety of locations to improve understanding of the processes controlling the mass balance of sea ice.

Techniques developed for the Arctic can contribute to this goal, but the unique characteristics of Antarctic sea ice make sustained observations even more challenging than in the Arctic. Most Antarctic sea ice is first-year ice that melts in summer. The short life-time of Antarctic sea ice means that ice-tethered platforms also have short life-times and therefore are not as cost-effective as in the Arctic. Antarctic sea ice is thinner, more mobile, with a heavier snow cover, and generally divergent – all characteristics that make sustained measurement (either in situ or by satellite) more difficult.

The relative importance of different physical processes varies across the Antarctic sea ice zone (e.g. from fast ice to the marginal ice zone, or from coastal polynyas to regions of multi-year ice). Sustained observations in each of these physical domains will require a different mix of measurement approaches.

Remote sensing (from satellites and/or aircraft) is the only way to collect observations of sea ice properties over broad scales, with satellites alone being able to provide regular, repetitive large-scale coverage. In situ observations supported by aircraft and autonomous underwater vehicles are critical for calibration and validation of satellite-derived parameters. Instruments important for the sea ice observing system include visible, infrared and passive microwave radiometers, synthetic aperture radars, radar scatterometers, and radar and laser altimeters. We need to ensure that satellite missions provide as continuous a record as possible and avoid gaps in the record in the future.

Over regional scales, sea ice thickness distribution can be measured by aircraft equipped with LIDAR. Algorithms used to convert surface elevation data into ice thickness need to be validated by concurrent observations of ice elevation, concentration and snow and ice thickness made by ship surveys. Photographic observations from airborne systems, towed electromagnetic induction sensors and snow radar also provide information on ice concentration, thickness and snow depths respectively.

Integrated ice observatories consisting of arrays of Ice Mass Balance Buoys, ice drift buoys, autonomous underwater vehicles, ice-tethered profilers and automatic weather stations are needed to provide simultaneous measurements of sea ice drift, deformation and growth, ice draft, ice-ocean interaction, and atmospheric forcing (Figure 22). Meteorological observations of atmospheric pressure, wind speed and direction are required as are upper ocean data on ocean heat and freshwater fluxes, swell and wave height (Table 5).

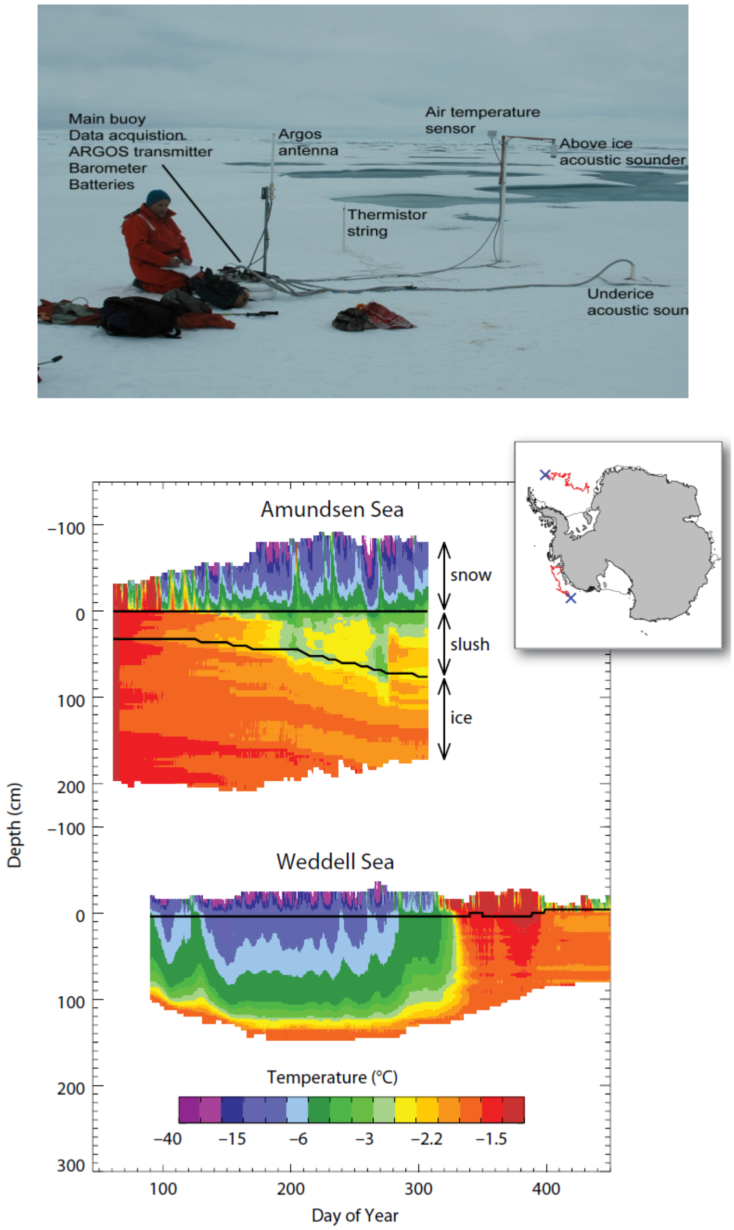


Figure 22: Example of an integrated sea ice observing array to make simultaneous measurements of sea ice, snow, atmosphere and ocean. Photo courtesy of Don Perovich. Bottom panel: internal sea ice temperature changes measured by ice mass balance buoys deployed in sea ice floes in the Weddell and Amundsen Seas, February 2009. Reproduced from Figure 4 of Maksym et al. (2012). .

Table 5: Platforms contributing to sustained measurements of sea ice and ice-ocean-atmosphere interaction.

Platform	Sampling requirements
Sea ice mass balance buoys	Air-ice-ocean measurements of T, snow and ice thickness, thermal structure, wave properties and barometric pressure. Most value gained by combining the top 4 platforms in this table into an integrated ice-ocean-atmosphere observing platform.
Ice-tethered profilers	Most cost-effective in multi-year ice. Development of ability to melt out and freeze in again the following winter would increase duration and cost-effectiveness. T, S and velocity.
Air-sea flux stations	On moorings, islands and ships. Wind speed/direction, humidity, air temperature, pressure, solar radiation, and ice floe rotation.
Turbulence sensors at ice-ocean interface	Deploy as part of integrated sea ice mass balance array. Measurements of turbulent microstructure.
Ice thickness sonar on floats, moorings and gliders/AUVs/submarines	Requires technology development to infer ice thickness from floats. Acoustic measurements of ice thickness.
Ice stations	Extended process studies with simultaneous measurements of ocean, ice and atmosphere.
Hydrographic sections	Surface meteorological observations should be made on GO-SHIP full-depth repeat hydrography lines wherever possible. These should include wind speed and direction (relative to the ship and corrected to absolute), air temperature and humidity, sea surface temperature, rainfall, barometric pressure, incoming shortwave and longwave radiation (see Bradley and Fairall, 2006).
Underway ship-based observations	Visual observations of sea ice characteristics while underway (sea ice and snow thickness), including automated approaches (e.g. digital ice cameras with image processing). Sea surface temperature and salinity from thermosalinograph,

	underway chlorophyll a, fluorescence, nutrients, and pCO2. All ships transiting sea ice zone including ships of opportunity (resupply and tourist vessels) whereever possible.
Airborne observations	Measurements of ice and snow thickness (e.g. EM, lidar), sea ice concentration. Airplanes, helicopters, UAVs.
Remote sensing	In situ observations essential for validation and calibration.
Meteorological sensors on ships	As per Shipboard Automated Meteorological and Oceanographic System (SAMOS).

Air-sea fluxes

Bourassa et al. (2013) offer recommendations for improving surface fluxes at high latitudes (Figure 23). An expanded network of standard meteorological measurements is needed, such as those collected by the Shipboard Automated Meteorological and Oceanographic System (SAMOS) program. Ships transiting the sea ice zone and weather stations on islands or continents are likely to be the primary source of such data (Table 6). As existing parameterizations are uncertain, direct measurements of fluxes are also urgently needed. Direct flux measurements can be made from ships and aircraft, with unmanned aerial vehicles (UAVs) likely to play an increasingly important role. Limited-duration process studies are needed to improve understanding of the coupled interactions between ocean, ice and atmosphere that determine air-sea exchange. Time series of fluxes derived from fixed-point moorings, such as the Australian Southern Ocean Flux Station (Schulz et al., 2012), can be of great value for validation of flux products, but are unlikely to be feasible within the ice-covered oceans.

In situ observations alone will never provide sufficient spatial and temporal coverage to determine air-sea fluxes in the sea ice zone. Improvements in the ability to derive flux information from satellite observations are needed. Present satellite sensors can measure many of the relevant variables, including wind stress (open ocean only), sea surface temperature, sea ice concentration, and near-surface air temperature and humidity. However, new satellite missions dedicated to turbulent flux measurements are likely needed to provide the desired accuracy. A regional reanalysis focused on Antarctica and the Southern Ocean, and incorporating an expanded in situ and remotely sensed data set, is likely to provide more accurate flux estimates than present global reanalyses.

Figure 23: Schematic of surface fluxes and related processes for high latitudes. Radiative fluxes are both shortwave (SW) and longwave (LW). Surface turbulent fluxes are stress, sensible heat (SHF) and latent heat (LHF). Ocean surface moisture fluxes are precipitation and evaporation (proportional to LHF). Processes specific to high-latitude regimes can strongly modulate fluxes. These include strong katabatic winds, effects due to ice cover and small-scale leads and polynyas, air-sea temperature differences that vary on the scale of eddies and fronts, deep and bottom water formation, and freshwater input associated with blowing snow. (Bourassa et al., 2013).

Table 6: Platforms contributing to sustained measurements of air-sea fluxes

Platform	Sampling requirements
Meteorological sensors on ships	As per SAMOS.
Direct flux measurements	Needed to improve parameterisations of air-sea fluxes from met measurements. Direct flux measurements can be made from ships, aircraft and UAVs.
Automatic weather stations	Expand array of AWS on coastline and islands.
Remote sensing	Dedicated air-sea flux missions?
Antarctic reanalysis	Assimilation of in situ and remotely sensed observations in a regional, high resolution Antarctic reanalysis is needed.

5. Path to Implementation

The present document articulates the scientific case for sustained under-ice observations in the Southern Ocean and provides a strategy and design for the observing system. The strategy does not provide a detailed implementation plan. The workshop concluded that implementation of the strategy will be most effectively carried out at regional level. A coalition of nations and scientists working in a particular region will be best-placed to design and implement the under-ice observing system for each region. Such regional domains might include, for example, the Ross Sea, Amundsen/Bellingshausen Sea, West Antarctic Peninsula, Weddell Sea, Prydz Bay, and the Wilkes Land coast, among others. The open ocean domain is best addressed on a circumpolar basis. International coordination and collaboration will be critical to implement the under-ice observing system. SOOS is well-placed to play this role. As with other components of the global ocean observing system, the bulk of the funding for the under-ice observing system will likely come from national research agencies.

The implementation of the under-ice observing system must exploit synergies with other components of the global ocean observing system (e.g. Argo, GO-SHIP, GEOTRACES, and satellite missions). Measurements in the sub-ice shelf cavity should be integrated with on-ice measurements (e.g. from phase sensitive radar). The focus of this document is on observations, but modelling has a critical role to play and needs to be well-integrated from the start. In particular, models will be needed to interpolate between sparse observations, to test hypotheses, and for projections of future change. In turn, the observations discussed here are essential for model testing and improvement.

SOOS should play an overall coordination and facilitation role, in conjunction with the CLIVAR/CliC/SCAR Southern Ocean Panel. The SOOS SSC may define a set of overall metrics to allow progress towards implementation of the observing system to be tracked. The SOOS office should provide a clearing-house for regional implementation plans and updates on new technological developments relevant to under-ice observing. The SOOS SSC should take a lead role in identifying gaps in the developing observing system and identify strategies to help fill them.

This first workshop on under-ice observing focused on the physical climate system. Sustained observations of biogeochemistry and biology are also critical, but even more challenging than the physical observations discussed here. Subsequent workshops are needed to design an under-ice observing system for biology and biogeochemistry. A biological and biogeochemical observing system will likely build on the foundation provided by the physical observing system outlined here and exploit the rapid developments in sensors for biology and biogeochemistry presently underway.

6. Summary

Interactions between the ocean, atmosphere and cryosphere at high southern latitudes have global significance. However, a lack of observations of the ocean beneath Antarctic sea ice and ice shelves has slowed progress in understanding these ocean-ice-atmosphere interactions and their potential sensitivity to change. An under-ice observing system to fill the largest blind spot in the global ocean observing system is essential to improve understanding of climate, biogeochemical cycles and sea level rise.

The sampling needs and opportunities are different in each domain of the high latitude Southern Ocean (the open ocean shallower than 2000 m, the deep ocean, the continental shelf and slope, sub-ice shelf cavities, and ocean-ice-atmosphere interactions in the surface layer). A different mix of platforms is therefore needed in each domain. Specific recommendations for each domain are presented in the Tables in Section 4.

Advances in technology now allow sustained observations of the ocean beneath sea ice and ice shelves to be made. A combination of platforms will be needed. Many key components of the observing system are available now , including ice-capable profiling floats, oceanographic sensors deployed on seals, ice-tethered profilers, sea-ice mass balance buoys, gliders and submersibles, ship-based hydrography, and moorings. However, these platforms have often been used in isolation rather than as part of an integrated system. A coordinated approach is needed to realise the full benefit of investment in ocean observing platforms and to provide ocean measurements on the spatial and temporal scales needed to address the key scientific questions identified in Section 3.

In addition, some critical variables cannot yet be sampled in a sustained manner using present technology. Advances are needed in the use of acoustics for data telemetry, navigation of autonomous platforms, and tomography in sub-ice shelf cavities. Profiling floats designed for sampling of the continental shelf are also required. Long-duration moorings with data telemetry would increase the cost-effectiveness of moored arrays. New satellite instruments hold promise for measurements of snow and ice thickness from space, but depend critically on in situ observations for calibration and validation. Further development of data-assimilating models is needed to fully exploit the observations, to help design the observing system, and to interpolate across gaps in the array.

7. References

Allison, I. (2003). The AMISOR Project: ice shelf dynamics and ice-ocean interaction of the Amery Ice Shelf. *Forum for Research into Ice shelf-ocean interactions (FRISP) Report No 14.*

Aoki, S., S.R. Rintoul, S. Ushio, S. Watanabe, and N.L. Bindoff (2005). Freshening of the Adélie Land Bottom Water near 140˚E, *Geophys. Res. Lett., 32*, L23601, doi:10.1029/2005GL024246.

Bamber, J. L., D. G. Vaughan & I. Joughin (2009). Widespread complex flow in the interior of the Antarctic Ice Sheet. *Science*, 287, 1248-1250, doi:10.1126/science.287.5456.1248

Bintanja, R., G. J. van Oldenborgh, S. S. Drijfout, B. Wouters & C.A. Katsman (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, doi:10.1038/NGEO1767.

Böning, C. W., A. Dispert, M. Visbeck, S.R. Rintoul, and F.U. Schwarzkopf (2008). The response of the Antarctic Circumpolar Current to recent climate change. *Nature Geoscience*, 1, 864–869, doi:10.1038/ngeo362.

Bourassa, M. A., Sarah T. Gille, Cecilia Bitz, David Carlson, Ivana Cerovecki, Carol Anne Clayson, Meghan F. Cronin, Will M. Drennan, Chris W. Fairall, Ross N. Hoffman, Gudrun Magnusdottir, Rachel T. Pinker, Ian A. Renfrew, Mark Serreze, Kevin Speer, Lynne D. Talley and Gary A. Wick, (2013). High-latitude ocean and sea ice surface fluxes: Challenges for climate research. *BAMS*, 403-423.

Bradley, F. and C. Fairall (2006). A guide to making climate quality meteorological and flux measurements at sea. *NOAA Technical Memorandum,* OAR PSD-311, Earth System Research Laboratory, Physical Sciences Division, Boulder, Colorado, USA, 81 pp.

Chen, J.L., C.R. Wilson, D. Blankenship, and B.D. Tapley (2009). Accelerated Antarctic ice loss from satellite gravity measurements. *Nature Geoscience*. 2, 859-862, doi: 10.1038/NGEO694.

De Angelis, H. and P. Skvarca (2003). Glacier surge after ice shelf collapse. *Science*. 299, 1560-1562, DOI: 10.1126/science.1077987.

Depoorter, M. A., J. L. Bamber, A. Griggs, J. T. M. Lenaerts, S. R. M. Ligtenberg, M. R. van den Broeke & G. Moholdt (2013). Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature*, 502, 89-83, doi:10.1038/nature12567.

Dupont, T.K. and R.B. Alley (2005). Assessment of the importance of ice-shelf buttressing to ice-sheet flow. *Geophysical Research Letters*, 32, L04503, doi:10.1029/2004GL022024, 2005.

Durack, P. J., & Wijffels, S. E. (2010). Fifty-year trends in global ocean salinities and their relationship to broad-scale warming. *Journal of Climate*, 23, 4342-4362.

Durack, P. J., P.J. Gleckler, F.W. Landerer and K.E. Taylor (2014). Quantifying estimates of long-term upper ocean warming. *Nature Geoscience*, 4, 999-1005, doi:10.1038/ nclimate2389.

Dutrieux, P., J. De Rydt, A. Jenkins, P. R. Holland, H. K. Ha, S. H. Lee, E. J. Steig, Q. Ding, E. P. Abrahamsen & M. Schröder (2014). Strong sensitivity of Pine Island Ice-Shelf melting to climatic variability. *Science*, 343, 174-178, doi:10.1126/science.12443431

Favier, L., G. Durand, S. L. Cornford, G. H. Gudmundsson, O. Gagliardini, F. Gillet-Chaulet, T. Zwinger, A. J. Payne & A. M. le Brocq (2014). Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change*, 4, 117-121,doi:10.1038/nclimate2094.

Fedak, M.A. 2013. The impact of animal platforms on polar ocean observation. *Deep-Sea Research Part II-Topical Studies in Oceanography.*88-89 (SI), 7-13, doi:10.1016/j.dsr2.2012.07.007.

Flament, T. and F. Rémy (2012). Dynamic thinning of Antarctic glaciers from along-track repeat radar altimetry. *Journal of Glaciology*, 58 (211), 830-840.

Fretwell, P., H.D. Pritchard, D.G. Vaughan, J.L. Bamber, N.E. Barrand, R. Bell, C. Bianchi, R.G. Bingham, D.D. Blankenship and G. Casassa (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, 7, 375-393, doi:10.5194/tc-7-375-2013.

Giles, A.B., R.A. Massom, P. Heil and G. Hyland (2011). Semi-automated feature-tracking of East Antarctic sea ice from Envisat ASAR imagery. *Remote Sensing of Environment*, 115 2267-2276, doi:10.1016/j.rse.2011.04.027.

Gille, S. T. (2008). Decadal-scale temperature trends in the Southern Hemisphere ocean. *Journal of Climate*, 21, 4749-4765.

Goosse, H. and V. Zunz (2014). Decadal trends in the Antarctic sea ice extent ultimately controlled by ice-ocean feedback. *The Cryosphere*, 8, 453-470, doi:10.5194/tc-8-453-2014.

Gordon, A. (1986). Interocean exchange of thermocline water. *Journal of Geophysical Research-Oceans*, 91(C4), 5037-5046, DOI: 10.1029/JC091iC04p05037.

Gwyther, D.E., B.K. Galton-Fenzi, J.R. Hunter and J.L. Roberts (2014). Simulated melt rates for the Totten and Dalton ice shelves. *Ocean Science*, 10, 267-279, doi:10.5194/os-10-267-2014.

Hellmer, H. H. (2004). Impact of Antarctic ice shelf basal melting on sea ice and deep ocean properties. *Geophysical Research Letters*, 31, L10307 , DOI: 10.1029/2004GL019506.

Hellmer, H., F. Kauker, R. Timmerman, J. Determann and J. Rae (2012). Twenty-first century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. *Nature*, 485, 225-228, doi:10.1038/nature11064.

Helm, K. P., Bindoff, N. L., Church, J. A. (2010). Changes in the global hydrological-cycle inferred from ocean salinity. *Geophysical Research Letters*, 37, doi:10.1029/2010GL044222.

Holland, P. R., & Kwok, R., 2012. Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*, 5, 872-875.

Hood, M. (ed). (2009). Ship-based Repeat Hydrography: A Strategy for a Sustained Global Programme. *IOC Technical Series*, 89. IOCCP Reports, 17. ICPO Publication 142.),UNESCO. Intergovernmental Oceanographic Commission of UNESCO and the International CLIVAR Project Office.

Jacobs, S.S. and C.F. Giulivi, (2010), Large multidecadal salinity trends near the Pacific-Antarctic continental margin, *J. Climate*, 23, 4508-4524, doi:10.1175/2010JCLI3284.1.

Jacobs, S.S., A.L. Gordon and J.L. Ardai Jr. (1979). Circulation and melting beaneath the Ross Ice Shelf. Science. 203 (4379), 439-443, doi: :10.1126/science.203.4379.439.

Jacobs, S. S., H. H. Hellmer, C. S. M. Doake, A. Jenkins and R. M. Frolich, (1992). Melting of Ice Shelves and the Mass Balance of Antarctica*. Journal of Glaciology*, 38 (130), 375-387.

Jacobs, S. S., A. Jenkins, C.F. Giulivi, and P. Dutrieux (2011). Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience*, 4, 519-523.

Jacobs, S.S., C. Giulivi, P. Dutrieux, E. Rignot, F. Nitsche and J. Mouginot (2013). Getz Ice Shelf melting response to changes in ocean forcing. *Journal of Geophysical Research-Oceans*, 118, 4152-4168, doi:10.1002/jgrc.20298.

Jenkins, A., Dutrieux, P., Jacobs, S. S. McPhail, S. D., Perrett, J. R., Webb, A. T., & White, D. (2010). Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. *Nature Geoscience*, 3, 468-472.

Joughin, I. and L. Padman (2003). Melting and freezing beneath Filchner-Ronne Ice Shelf, Antarctica. *Geophysical Research Letters*. 30, 1477, doi:10.1029/2003GL016941.

Joughin, I., R.B. Alley and D.M. Holland (2012). Ice-sheet response to oceanic forcing. *Science*, 338, 1172-1176, DOI: 10.1126/science.1226481.

Joughin, I., B.E. Smith and B. Medley (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science*, 344, 735-738, DOI: 10.1126/science.1249055.

Kennicutt, M., S.L. Chown, J. Cassano, D. Liggett, R. Massom, L. Peck, S.R. Rintoul, J. Storey, D. Vaughan, T. Wilson and W.J. Sutherland (2014). Six priorities for Antarctic Science. *Nature*, 512, 23-25.

Khatiwala S., Primeau, F., & Hall, T. (2009). Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature*, 462, 346-349.

Khatiwala, S, Tanhua, T, Fletcher, Gerber, M, Doney, SC, Graven, HD, Gruber, N, McKinley, GA, Murata, A, Rios, AF & Sabine, CL (2013). Global ocean storage of anthropogenic carbon. *Biogeosciences,* 10, 2169-2191 ,DOI: 10.5194/bg-10-2169-2013

Khazendar, A., M. P. Schodlok, I. Fenty, S. R. M. Ligtenberg, E. Rignot & M. R. van den Broeke, 2013. Observed thinning of Totten Glacier is linked to coastal polynya variability. *Nature Communications*, doi:10.1038/ncomms3857.

Kohout, A. L., M. J. M. Williams, S. M. Dean & M. H. Meylan, 2014. Storm-induced sea-ice breakup and the implications for ice extent. *Nature*, 509, 604-609, doi:10.1038/nature13262

Le Quéré, C, C. Rodenbeck, E. T. Buitenhuis, T. J. Conway, R. Langenfelds, R., A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett & M. Heimann 2007: Saturation of the southern ocean CO2 sink due to recent climate change. *Science*, 316. doi:10.1126/science.1136188.

Levitus, S. , J. I. Antonov, T. P. Boyer, O. K. Baranova, H. E. Garcia, HE, R. A. Locarnini, A. V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, M. M. Zweng (2012). World ocean heat content and thermosteric sea level change (0-2000). *Geophysical Research Letters,* 39, L10603, doi:10.1029/2012GL051106.

Li, X., D.M. Holland, E.P. Gerber and C. Yoo. (2014). Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature*, 505, 538-542, doi:10.1038/nature12945.

Lumpkin, R. and K. Speer (2007). Global Ocean Meridional Overturning. *Journal of Physical Oceanography*, 37, 2550–2562, doi: http://dx.doi.org/10.1175/JPO3130.1.

Maksym, T., S.E. Stammerjohn, S. Ackley and R. Massom (2012). Antarctic sea ice - A polar opposite? *Oceanography*, 25 (3), 140-151, http://dx.doi.org/10.5670/oceanog.2012.88.

Marshall, G.J. (2003). Trends in the Southern Annular Mode from Observations and Reanalyses. *Journal of Climate*, 16, 4134-4143.

Marshall, J., & Speer, K. (2012). Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nature Geoscience*, 5, 171-180.

Massom, R., A.B. Giles, H.A. Fricker, R.C. Warner, B. Legrésy, G. Hyland, N. Young, A.D. Fraser (2010). Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: Another factor in ice sheet stability? *Journal of Geophysical Research*, 115, C12027, DOI: 10.1029/2009JC006083.

Massom, R.A., P. T. Harris, K. Michael, and M.J. Potter (1998). The distribution and formative processes of latent heat polynyas in East Antarctica. *Annals of Glaciology, 27,* 420-426.

McMillan, M., A. Shepherd, A. Sundal, K. Briggs, A. Muir, A. Ridout, A. Hogg and D. Wingham (2014). Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters. 41 (11), 3899-3905, doi:10.1002/2014GL060111.

Meijers, A.J.S., N. L. Bindoff and S. R. Rintoul (2011). Frontal movements and property fluxes; contributions to heat and freshwater trends in the Southern Ocean. Journal *of Geophysical Research – Oceans*, 116, C08024, doi 10.1029/2010JC006832.

Miller, K.G., J.D. Wright, J.V. Browning, A. Kulpecz, M. Kominz, T.R. Naish, B.S. Cramer, Y. Rosenthal, W.R. Peltier and S. Sosdian (2012). High tide of the warm Pliocene: implications of global sea level for Antarctic deglaciation. *Geology*, 40 (5), 407-410, doi: 10.1130/G32869.1.

Morrison, A. K., and A. McC. Hogg (2013) On the Relationship between Southern Ocean Overturning and ACC Transport. *J. Phys. Oceanogr.*, 43, 140–148. doi:http://dx.doi.org/10.1175/JPO-D-12-057.1.

National Research Council (2011). Future Science Opportunities in Antarctica and the Southern Ocean. National Academies Press, Washington D.C., U.S.A, 195 pp.

Nicholls, K.W. and A. Jenkins (1993) Temperature and salinity beneath Ronne ice shelf, Antarctica. *Journal of Geophysical Research-Oceans,* 98 (C12), 22553-22568.

Orsi, A. H. and T. Whitworth III (2005). *Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE). Volume I: Southern Ocean* (eds. M. Sparrow, P. Chapman and J. Gould), International WOCE Project Office, Southampton, U.K., ISBN 0-904175-49-9.

Parkinson, C.L. and D.J. Cavalieri (2012). Antarctic sea ice variability and trends, 1979-2010. *The Cryosphere*, 6, 871-880.

Pritchard, H. D., Arthern, R. J., Vaughan, D. G. & Edwards, L. A. (2009). Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature* 461, 971–975 doi:10.1038/nature08471.

Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., Van den Broeke, M. R., & Padman, L. (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, *484*, 502-505. doi:10.1038/nature10968.

Purkey, S.G., and G.C. Johnson (2010), Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *J. Climate*, *23*, 6336-6351, doi:10.1175/2010JCLI3682.1.

Purkey, S.G., and G.C. Johnson (2012), Global Contraction of Antarctic Bottom Water between the 1980s and 2000s. *J. Climate, 25,* 5830-5844, doi:10.1175/JCL-D-11-00612.1.

Purkey, S.G. and G.C. Johnson (2013). Antarctic Bottom Water warming and freshening: Contributions to sea level rise, ocean freshwater budgets, and global heat gain, *J. Climate,* 26 (16), 6105-6122, doi:10.1175/JCLI-D-12-00834.1.

Rhein, M., S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, G. C. Johnson, S. A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L. D. Talley and F. Wang (2013). Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 255-315.

Rignot, E. and S.S. Jacobs (2002). Rapid bottom melting widespread near Antarctic ice sheet grounding lines. *Science*, 296 (5575), 2020-2023. DOI: 10.1126/science.1070942.

Rignot, E., Velicogna, I., Van den Broeke, M. R., Monaghan, A., & Lenaerts, J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.,* 38, L05503.

Rignot, E., S. Jacobs, J. Mouginot & B. Scheuchl, 2013. Ice-shelf melting around Antarctica. Science, 3412, 266-270, doi:10.1126/science.1235798.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi and B. Scheuchi (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters*, 41(10), 3502-3509, DOI: 10.1002/2014GL060140.

Rintoul, S.R. (2007), Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans. *Geophys. Res. Lett., 34,* L06606, doi:10.1029/2006GL028550.

Rintoul, S. R. (2011). The Southern Ocean in the Earth System. In: Science Diplomacy: Antarctica, Science and the Governance of International Spaces. Berkman, P.A., Lang, M.A., Walton, D.W.H., and Young O.R. (Eds.). Smithsonian Institution Scholarly Press, Washington, 175-187.

Rintoul, S. R. and A. C. Naveira Garabato (2013). Chapter 18: Dynamics of the Southern Ocean Circulation. In: Siedler, G., Griffies, S., Gould, J. and Church, J. (Eds.): Ocean Circulation and Climate, 2nd Ed. A 21st century perspective, International Geophysics Series, Volume 103, ISBN: 9780123918512 Academic Press, 2013.

Rintoul, S.R., M. Sparrow, M.P. Meredith, V. Wadley, K. Speer, E. Hofmann, C. Summerhayes, E. Urban and R. Bellerby. (2012). The Southern Ocean Observing System: Initial Science and Implementation Strategy, SOOS Project Office, University of Tasmania, Australia, 74 pp.

Roberts, J.L., R.C. Warner, D. Young, A. Wright, T.D. van Ommen, D.D. Blankenship, M. Siegert, N.W. Young, I.E. Tobacco, A. Forieri, A. Passerini, A. Zirizzotti and M. Frezzotti. (2011). *Cryosphere*, 5 (3), 551-560, doi:10.5194/tc-5-551-2011.

Robertson, R.A. (2013). Tidally induced increases in melting of Amundsen Sea ice shelves, *Journal of Geophysical Research: Oceans*, 118 (6), 3138-3145, doi: 10.1002/jgrc.20236.

Roquet, F., C. Wunsch, G. Forget, P. Heimbach, C. Guinet, G. Reverdin, J.-B Charassin, F. Bailleul, D.P. Costa, L.A. Huckstadt, K.T. Goetz, K.M. Kovacs, C. Lydersen, M. Biuw, O. A. Nøst, H. Bornemann, J. Ploetz, M. N. Bester, T. McIntyre, M.C. Muelbert, M.A. Hindell, C.R. McMachon, G. Williams, R. Harcourt, I.C. Field, L. Chafik, K.W. Nicholls, L. Boehme and M. Fedak. (2013). Estimates of the Southern Ocean general circulation improved by animal-borne instruments. *Geophysical Research Letters*, 40, 1-5, doi:10.1002/2013GL058304.

Rye, C. D., A. C. Naveira Garabato, P. R. Holland, M. P. Meredith, A. J. G. Nurser, C. W. Hughes, A. C. Coward and D. J. Webb (2014). Rapid sea-level rise along the Antarctic margins in response to increased glacial discharge. *Nature Geoscience,* DOI: 10.1038/NGEO2230

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.H. Peng, A. Kozyr, T. Ono, A.F. Rios (2004). Oceanic sink for anthropogenic CO_2. *Science*, 305, 367-371.

Sallée, J. B., R. Matear, S. R. Rintoul and A. Lenton, 2012. Surface to interior pathways of anthropogenic CO_2 in the southern hemisphere oceans. Nature Geoscience, 5,579-584, doi:10.1038/ngeo1523.

Sarmiento, J.L., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S.A. Spall and R. Stouffer (2004). Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles*, 18 GB3003, doi:10.1029/2003GB002134.

Schoof, C. (2007). Ice sheet grounding line dynamics: Steady states, stability and hysteresis. *Journal of Geophysical Research: Earth Surface(2003-2012).* 112, F03S28, doi:10.1029/2006JF000664.

Schmitz, W.J. (1995). On the interbasin-scale thermohaline circulation. *Reviews of Geophysics*, 33, 151-173, http://dx.doi.org/10.1029/95RG00879.

Schulz, E.W., S.A. Josley and R. Verein (2012). First air-sea flux mooring measurmenets in the Southern Ocean. *Geophysical Research Letters*, 39, L16606, doi:10.1029/2012GL052290, 2012.

Sen Gupta, A. and M.H. England (2006). Coupled ocean-atmosphere-ice response to variations in the Southern Annular Mode. *Journal of Climate*, 19, 4457-4486.

Shimada, K., S. Aoki, K.I. Ohshima, and S.R. Rintoul (2012), Influence of Ross Sea bottom water changes on the warming and freshening of the Antarctic Bottom Water in the Australian-Antarctic Basin, *Ocean Sci., 8*, 419-432, doi:10.5194/os-8-419-2012.

Smethie, W. M. and S. S. Jacobs, 2005: Circulation and melting under the Ross Ice Shelf: estimates from evolving CFC, salinity and temperature fields in the Ross Sea. Deep-Sea Research Part I-Oceanographic Research Papers, 52(6): 959-978.

Sokolov, S. & S. R. Rintoul, 2009. The circumpolar structure and distribution of the Antarctic Circumpolar Current fronts. Part 2: Variability and relationship to sea surface height. *Journal of Geophysical Research – Oceans*, 114, C11, doi:10.1029/2008JC005248.

Speer, K., S. R. Rintoul, and B. Sloyan (2000) The Diabatic Deacon Cell. *J. Phys. Oceanogr.*, 30:3212--3222.

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 El Niño-Southern Oscillation and Southern Annular Mode. *Journal of Geophysical Research*, 113, C03S90, doi:10.1029/2007JC004269.

Stammerjohn, S., R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, *Geophysical Research Letters,* 39, L06501, doi:10.1029/2012GL050874.

Steig, E.J., Q. Ding, D.S. Battisti and A. Jenkins (2012). Tropical forcing of circumpolar deep water inflow and outlet glacier thinning in the Amundsen Sea embayment, West Antarctica. *Annals of Glaciology*, 53 (60), 19-28.

Swart, N.C. and J.C. Fyfe (2013). The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters*, 40(16), 4328-4332, DOI: 10.1002/grl.50820.

Talley, L.D. 2013. Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and transports. Oceanography 26(1):80–97, http://dx.doi.org/10.5670/oceanog.2013.07.

Tamura, T., G.D. Williams, A.D. Fraser and K.I. Ohshima (2008). Potential regime shift in decreased sea ice production after the Mertz Glacier calving. Nature Communications, 3:826, DOI:10.1038/ncomms1820.

Turner, J. and J. Overland (2009). Contrasting climate change in the two polar regions. *Polar Research* 28 (92), 146-164.

Turner, J., J.C. Comiso, G.J., Marshall, T.A. Lachlan-Cope, T.J. Bracegirdle, T. Maksym, M.P. Meredith, 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. *Geophysical Research* Letters, 36 (L08502), doi: 10.1029/2009GL037524.

van Wijk, E. M. and S. R. Rintoul, 2014. Freshening drives contraction of Antarctic Bottom Water in the Australian Antarctic Basin. *Geophysical Research Letters*, 41, doi:10.1002/2013GL058921.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang (2013). Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317-379.

Wåhlin, A., O. Kalén L. Arneborg, G. Björk, G. Carvajal, H. K. Ha, T. W. Kim , S. H. Lee, J. H. Lee, C. Stranne, 2013. The effect of wind forcing on the flow of warm deep water in a submarine trough on the Central Amundsen Shelf. Journal of Physical Oceanography, 43, 2054 - 2070.

Walker, D. P., M.A. Brandon, A. Jenkins, J.T. Allen, J.A. Dowedswell and J. Evans (2007). Oceanic heat transport onto the Amundsen Sea shelf through a submarine glacial trough. *Geophysical Research Letters* 34, L02602, doi:10.1029/2006GL028154.

Yang, X.-Y., R.X. Huang, and D.X. Wang (2007). Decadal changes of wind stress over the Southern Ocean associated with Antarctic ozone depletion. *Journal of Climate*, 20, 3395-3410, DOI: 10.1175/JCLI4195.1

Young, D.A., A.P. Wright, J.L. Roberts, R.C. Warner, N.W. Young, J.S. Greenbaum, D.M. Schroeder, J.W. Holt, D.E. Sugden, D.D. Blankenship, T.D. van Ommen and M.J. Siegert (2011). A dynamic early East Antarctic Ice sheet suggested by ice covered fjord landscapes. *Nature*, 474, 72-75, doi:10.1038/nature10114.

Workshop Participants

The participants at the Under Ice workshop are listed in the table below. The workshop ran over four days from the 22-25 Oct 2012. Experts in their field were invited to present on Days 1 and 2 (speakers indicated by *) which were open to the scientific community by registration of interest. Days 3 and 4 were restricted to invited participants divided into discussion groups allocated along the 3 key themes.

Participants (* presenters)	**Affiliation**	**Days 1-4**	**Days 1-2**
Steve Ackley *	University of Texas at San Antonio, USA	x	
Jessica Benthuysen	CSIRO, Australia		x
Nathan Bindoff	University of Tasmania, Australia	x	
Olaf Boebel *	Alfred Wegener Institute, Germany	x	
Lars Boehme *	University of St Andrews, UK	x	
Andy Bowen *	Woods Hole Oceanographic Institute, USA	x	
Eva Cougnon	IMAS, University of Tasmania, Australia		x
Matthew Dzieciuch *	SCRIPPS Institution of Oceanography, USA	x	
Ben Galton-Fenzi *	ACE CRC, Australia	x	
David Gwyther	IMAS, University of Tasmania, Australia		x
Ho Kyung Ha	Inha University, South Korea	x	
Craig Hanstein	CSIRO, Australia		x
Laura Herraiz-Borreguero *	Centre for Ice and Climate, Niels Bohr Institute, Univeristy of Copenhagen, Denmark	x	
Karen Heywood *	University of East Anglia, UK	x	
Katy Hill	IMOS, Australia		x
Mark Hindell *	IMAS, University of Tasmania, Australia	x	
David Holland *	New York University, USA	x	
Adrian Jenkins *	British Antarctic Survey, UK	x	
Alexander Klepikov *	Arctic and Antarctic Research Institute, Russian Federation	x	
Craig Lee *	University of Washington, USA	x	
SangHoon Lee *	Korean Polar Research Institute, South Korea	x	
Jiping Liu *	Chinese Academy of Sciences, China	x	
Mauricio Mata *	Federal University of Rio Grande Foundation, Brazil	x	
Andrew McMinn	IMAS, Australia		x
Walter Munk	SCRIPPS Institution of Oceanography, USA		x
Alberto Naveira Garabato*	National Oceanographic Centre, UK	x	
Louise Newman	SOOS office, Australia		
Keith Nicholls *	British Antarctic Survey, UK	x	
Max Nikurashin	IMAS, University of Tasmania, Australia		x
Kay Ohshima *	Hokkaido University, Institute of Low temperature Science, Japan (contributed but unable to attend)	x	
Alexander Orsi *	Texas A&M University, USA	x	
Svein Osterhus *	Bjerknes Centre for Climate Research, Norway	x	
Breck Owens *	Woods Hole Oceanographic Institute, USA	x	
Beatriz Pena-Molino	ACE CRC, Australia	x	
Helen Phillips	IMAS, University of Tasmania, Australia		x
Mark Pittard	IMAS, University of Tasmania, Australia		x
Steve Piotrowicz *	NOAA, USA	x	
Alan Poole	CSIRO, Australia		x

Steve Rintoul *	CSIRO, Australia; SOOS SSC member	x	
Stephen Riser *	University of Washington, USA	x	
Robin Robertson	University of New South Wales, Australia	x	
Tatsuru Sato	Hokkaido University, Institute of Low temperature Science, Japan	x	
Elizabeth Shadwick	ACE CRC, Australia		x
Graham Simpkins	University of New South Wales, Australia		x
Kevin Speer *	Florida State University, USA	x	
Fiona Taylor	University of Tasmania, Australia	x	
Ann Thresher	CSIRO, Australia		x
Bronte Tilbrook	CSIRO, Australia		x
John Toole *	Woods Hole Oceanographic Institute, USA	x	
Esmee van Wijk *	CSIRO, Australia	x	
Stefan Vogel	Australian Antarctic Division, Australia		x
Anna Wahlin *	University of Gothenburg, Sweden	x	
Susan Wijffels	CSIRO, Australia		x
Mike Williams *	NIWA, New Zealand	x	
Tony Worby	CSIRO, Australia		x
Changhyun Yoo	Courant Institute of Mathematical Sciences, USA	x	

The Southern Ocean Observing System is an initiative of the Scientific Committee for Oceanic Research (SCOR) and the Scientific Committee for Antarctic Research (SCAR). The SOOS International Project Office is hosted by the Institute of Marine and Antarctic Studies, University of Tasmania, Australia.