CHAPTER 8

Oceanography and sea ice in the Southern Ocean

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8.1 Introduction

The Arctic and the Antarctic are situated diametrically opposite each other on the planet, and their polar locations lead to them sharing some obvious similarities in climate and other characteristics. In some respects, however, their differences are more profound, and possibly the most significant of these is that the Arctic is fundamentally an ocean surrounded by land, whereas the Antarctic is a major continental landmass encircled by a vast and isolating ocean (Figure 8.1). This ocean – the Southern Ocean – has a profound influence on regional and global climate, on the glaciation of the Antarctic continent, and on biodiversity and ecosystem functioning.

The harsh environment and remoteness of Antarctica and the Southern Ocean were contributory factors in early Antarctic exploration being delayed compared with that in the Arctic, with the consequent scientific understanding that follows also lagging by comparison. It is thought that the first traveller who crossed the Arctic Circle and described their findings was the Greek Phytheas, around 325 BC, whereas Antarctic exploration progressed much more slowly, with James Cook crossing the Antarctic Circle on 17 January 1773. Scientific discovery in Antarctica progressed through the heroic age of exploration, with some early findings on the circulation of the Southern Ocean and the nature of the sea ice and icebergs that infest it. Often these studies were conducted for operational reasons, to assist in safe passage to, from and around Antarctica. Examples such as the sinking of Shackleton's ship *Endurance* in the Weddell Sea in 1915 demonstrate the need that these early explorers had for understanding of the behaviour of the Southern Ocean and its sea ice, and the limitations of that understanding.

It was the *Discovery Investigations* in the 1920s and 1930s that really marked the start of systematic scientific investigation into the Southern Ocean (e.g. Deacon, 1937). These were motivated by the recognition of a need to understand the functioning of the Southern Ocean ecosystem, some species of which (whales and seals) were commercially of immense value. These investigations included a large series of ship-based research expeditions (Figure 8.2), and, showing remarkable prescience, these early scientific investigations sought to understand the interdisciplinary functioning of the Southern Ocean, including ocean circulation, climate and sea ice, in order to better understand the life within it (Deacon, 1937, 1955).

Since the time of the *Discovery Investigations*, enormous progress has been made in understanding the Southern Ocean, and the role of sea ice in influencing its properties and determining its circulation is now better appreciated than ever. This understanding has been gained during a series of scientific experiments and long-term monitoring programmes, including the World Ocean Circulation Experiment (WOCE) in the 1990s (e.g. Ganachaud & Wunsch, 2000), which had a specific programmatic focus on the Southern Ocean (King, 2001).

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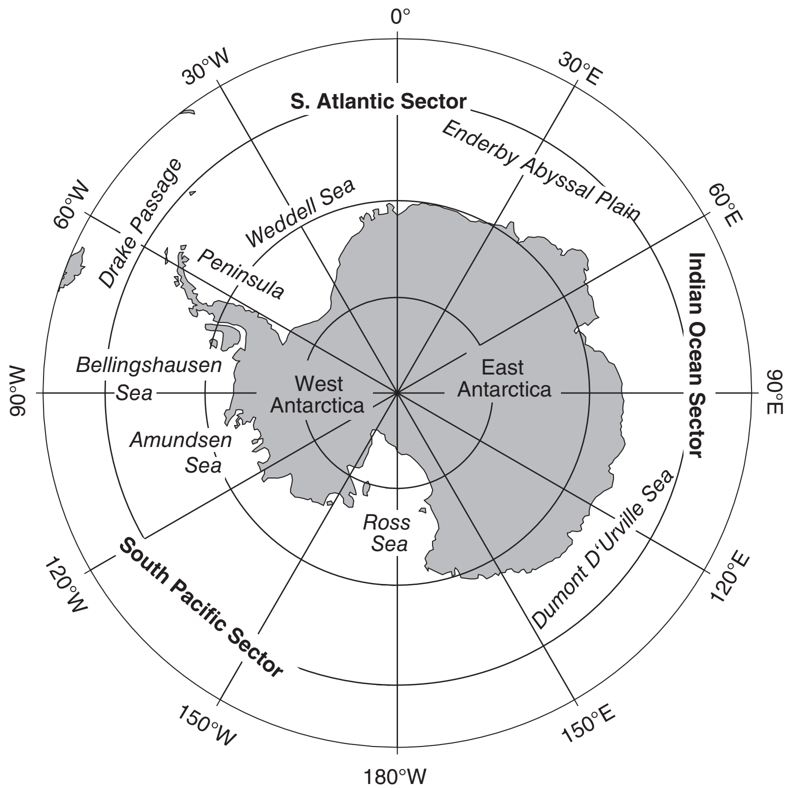


Figure 8.1 Map of Antarctica and the Southern Ocean, with selected place names marked.

Nonetheless, making progress in understanding the role of sea ice in structuring and controlling the Southern Ocean has remained challenging, in no small part due to the presence of the sea ice itself. Much of the research during WOCE and other programmes was conducted from research vessels, the vast majority of which are not icebreakers or ice-strengthened, and hence few of which could penetrate the Antarctic pack. There thus remains a dearth of direct observations concerning the interaction of the Southern Ocean with its seasonal and perennial sea ice cover, although with some very notable exceptions such as the landmark Ice Station Weddell expedition in 1992 (Muench & Gordon, 1995), and the ISPOL drift of the German ship R/V *Polarstern* in the Weddell Sea in 2006 (Hellmer et al., 2008).

Contemporary approaches to this problem are focusing on the progressively greater use of robotic instrumentation and autonomous (unmanned) ocean vehicles, some of which can be deployed into the ocean and navigated beneath the sea ice to collect data without the need for research vessels to attempt to access the pack directly. Great progress is being made, and significantly larger quantities of data are now being collected than ever before, enabling profound scientific advances across a range of disciplines. However, the ice-covered region of the Southern Ocean still remains the world's biggest data desert, and some of the most pressing scientific issues still require significantly more observational and research effort here to be fully addressed.

The purpose of this chapter is to provide an overview of some key aspects concerning how the sea ice around Antarctica shapes and influences the Southern Ocean's circulation and properties, how the ocean dictates the nature and behaviour of the sea ice, and collectively what the implications of these interactions are for larger-scale environmental issues. Without seeking to be exhaustive, we will highlight a few scientific areas of significant present activity, the current state of that research, and the emerging technologies that are

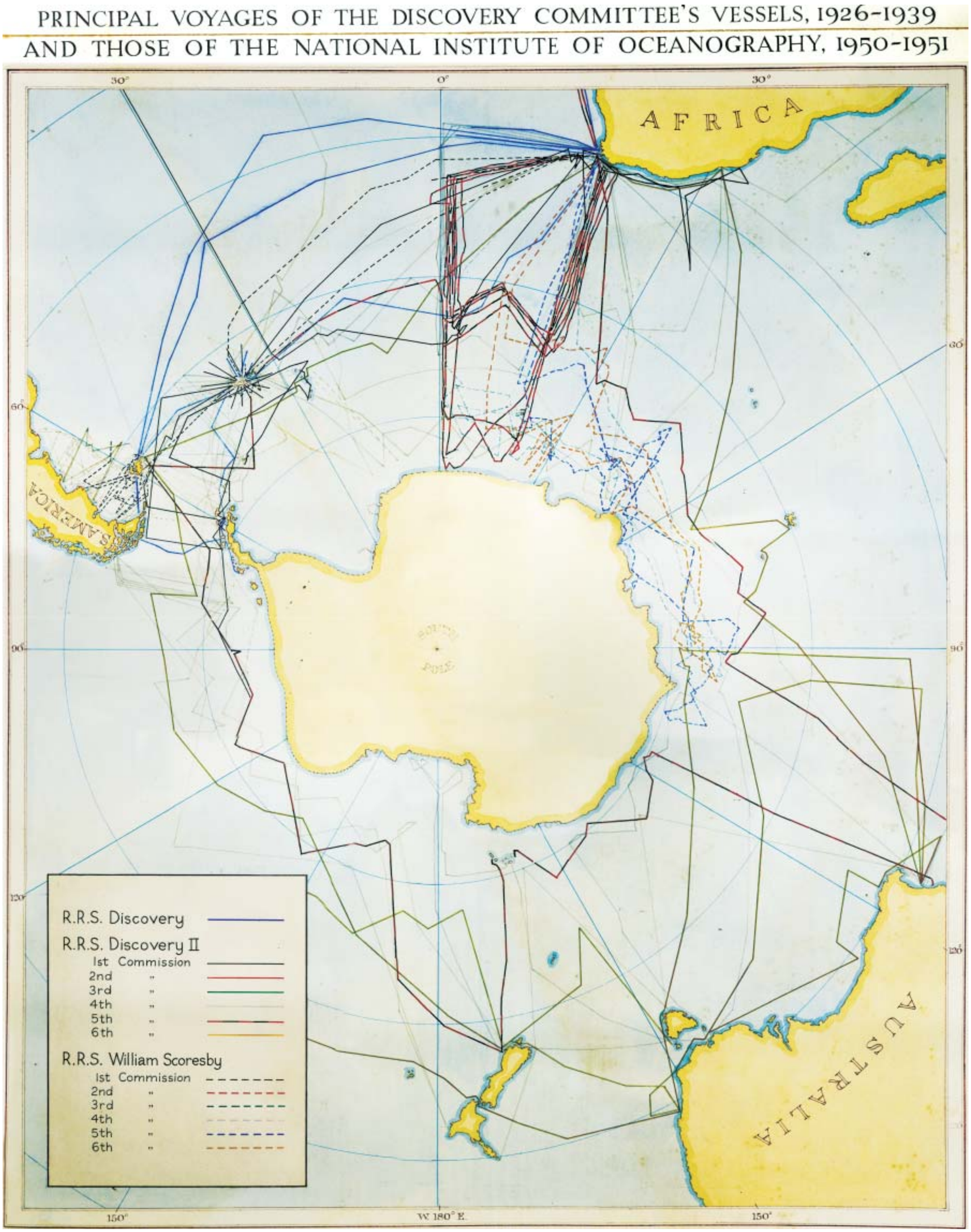


Figure 8.2 Map of the ship tracks undertaken during the *Discovery Investigations*, hand-drawn by E. Humphreys after the initial voyages of *Discovery* and *Discovery II*, and updated between the 1930s and 1950s. A monochrome reproduction of this appeared in Deacon (1955). Source: From Deacon, 1955. Reproduced with permission of John Wiley & Sons.

required to further these areas of investigation into the future.

8.2 Geographic and oceanographic setting of the Southern Ocean

The bathymetry that underlies the Southern Ocean is a mixture of comparatively smooth, oceanic abyssal plains of up to ~4000 m depth or deeper (e.g. the Weddell-Enderby Plain in the Atlantic sector), separated by much shallower and often convoluted ridge systems (Figure 8.3). The overall topographic configuration of the Southern Ocean is unique in the world, possessing a circumpolar channel that is open at all longitudes. This, combined with the strong westerly winds and buoyancy forcing that typifies the high latitudes, leads to the existence of the Antarctic Circumpolar Current (ACC; Figure 8.3; Rintoul et al., 2001).

The ACC is the largest current system in the world, continuously transporting approximately 130 Sv of water eastwards around Antarctica (1 Sv = 10^6 $m^3 s^{-1}$) (Meredith et al., 2011). It is a banded structure, consisting of relatively fast-moving jets separated by more quiescent zones of water. These jets coincide with oceanic fronts, namely (north to south), the

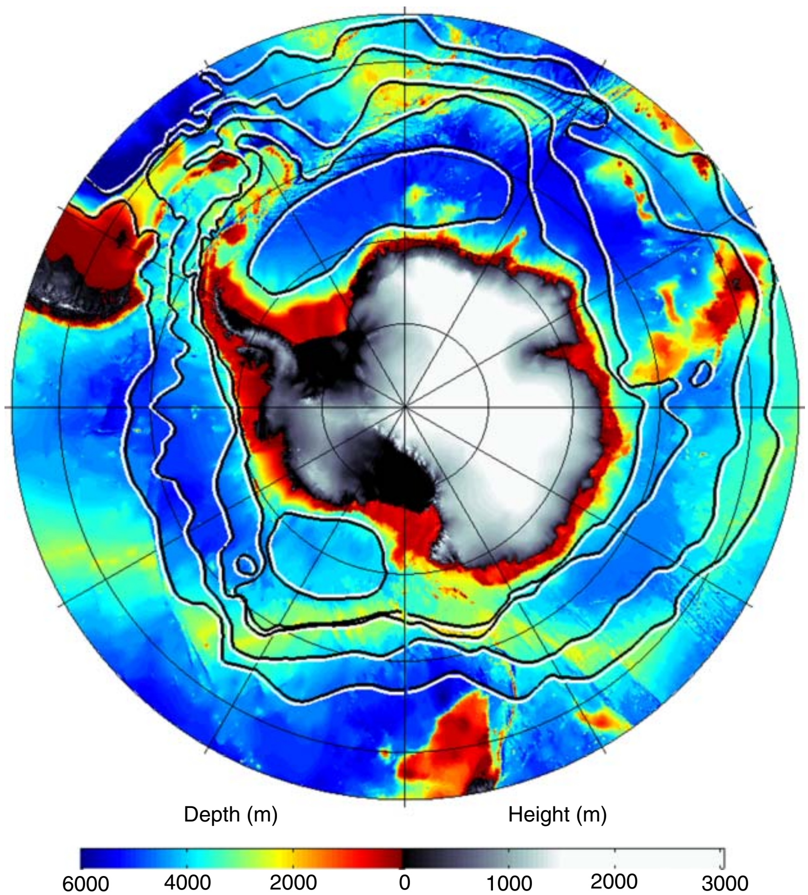


Figure 8.3 Bathymetry and topography of the Southern Ocean and Antarctica. Depths below sea level are coloured; heights above sea level are monochrome. Note the convoluted ridge systems, such as in and around Drake Passage (see Figure 8.1), separating wide expanses of oceanic abyssal plain. Also shown are schematic depictions of the fronts of the Antarctic Circumpolar Current (ACC) in the Southern Ocean, namely (north to south) the Subantarctic Front (SAF), the Polar Front (PF) and the Southern ACC Front (SACCF). South of the SACCF lies the Southern Boundary of the ACC. Frontal locations from Orsi et al. (1995). Poleward of the ACC lie sub-polar gyre systems, including the Weddell and Ross Gyres (marked).

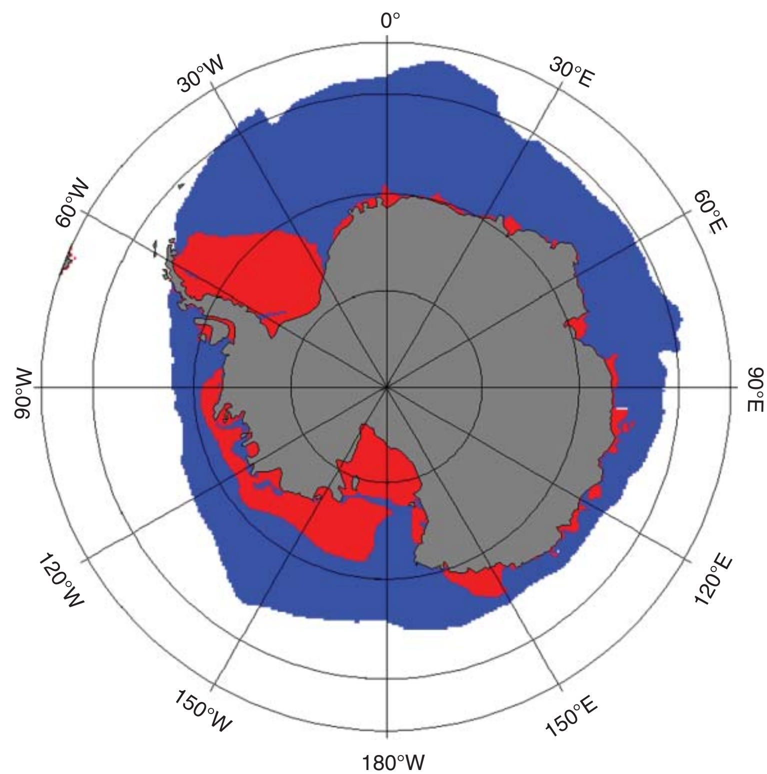


Figure 8.4 Climatological maxima and minima of the sea ice field around Antarctica, shown in blue and red, respectively.

Subantarctic Front, the Polar Front and the Southern ACC Front (Orsi et al., 1995). The southern edge of the ACC is marked by the Southern Boundary (Figure 8.3). Poleward of the ACC lie a series of sub-polar gyres, most notably in the Weddell Sea and Ross Sea (Figures 8.1 and 8.3). These transport a few tens of Sv cyclonically around the basins within which they reside, with the strongest parts of the circulation focused in boundary currents that lie adjacent to the periphery of the basins (Fahrbach et al., 1994).

The gyres are blanketed by sea ice in winter (Figure 8.4), which extends up to the southern part of the ACC during this season, with the sea ice edge being strongly steered by the path of the Southern Boundary (Figure 8.4, cf. Figure 8.3). The total ice coverage in the Southern Ocean reaches almost 19 million km^2 in the austral winter, compared with typically around 3 million km^2 in summer, a total range more than 1.5 times greater than the seasonal change in the Arctic. The perennial ice that remains in the Southern Ocean in winter typically inhabits the coastal regions and areas within the sub-polar gyres, most notably in the Weddell Sea (Figure 8.4).

In addition to the strong horizontal circulations in the Southern Ocean, and arguably of even more climatic importance, is a vigorous overturning circulation (Marshall & Speer, 2012). This is a key part of the global ocean overturning circulation, since the Southern Ocean is the main region within which deep waters are upwelled to the surface where they can exchange buoyancy with the atmosphere and be converted into both denser and lighter water masses (Rintoul et al., 2001). Sea ice is an important factor in the forcing of this overturning circulation and the formation of water masses, since it represents a key component of the buoyancy forcing in the Southern Ocean and a modulator of the wind stress imposed on the surface.

The overturning circulation in the Southern Ocean is shown schematically in Figure 8.5, where Circumpolar Deep Water (CDW; derived from the products of deep convection in the North Atlantic, and the most voluminous water mass of the ACC) is shown upwelling to the

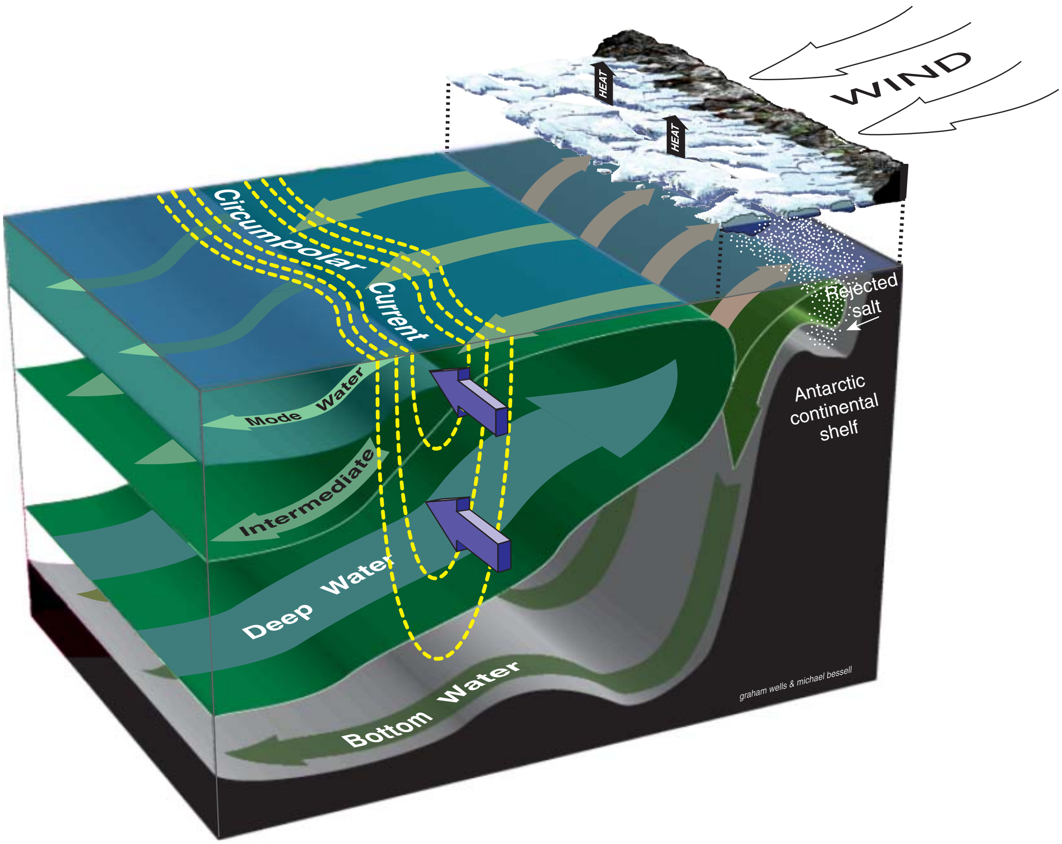


Figure 8.5 Schematic of the overturning circulation in the Southern Ocean. Circumpolar Deep Water upwells to the surface and is reprocessed into both lighter (mode and intermediate) waters and denser (bottom) waters. Source: From Rintoul, 2000. Reproduced with permission of the Royal Society of Tasmania, http://eprints.utas.edu.au/13587/.

surface in the vicinity of the ACC. One component of the CDW is converted by air–sea–ice interaction into lighter (mode and intermediate) water masses (McCartney, 1977), whilst a different component spreads southwards via the sub-polar gyres and becomes involved in the production of dense waters that sink to the seabed and spread out to fill much of the global abyss (Johnson, 2008). Such generalized views of Southern Ocean overturning are necessarily conceptual, and significant factors are not incorporated; nonetheless they remain useful guides to understanding.

Separating the ACC and the gyres from the continent itself are the shelf and slope regions of Antarctica. The Antarctic shelf is deeper than many shelf regions in the world, at typically a few hundred metres depth, and is dissected in many places by glacially scoured canyons. The waters on the Antarctic shelf are often subcategorized into those residing in a 'warm' sector (primarily the Bellingshausen and Amundsen seas; Figure 8.1), and those in a 'cold' sector (Figure 8.6; see also Clarke et al., 2009; Schmidtko et al., 2014). To leading order, this pattern is determined by the proximity of the ACC to the shelf. In the warm sector, the ACC lies immediately adjacent to the shelf, and hence warm waters can penetrate onto the shelf in relatively unmodified form, with the cross-shelf canyons being especially efficacious in enabling this transport (e.g. Martinson, 2011). In other sectors, the sub-polar gyres separate the warm waters of the ACC from the shelf regions, and hence any waters that can penetrate onto the shelf carry substantially less heat. This has a profound impact on ocean and atmospheric climate in

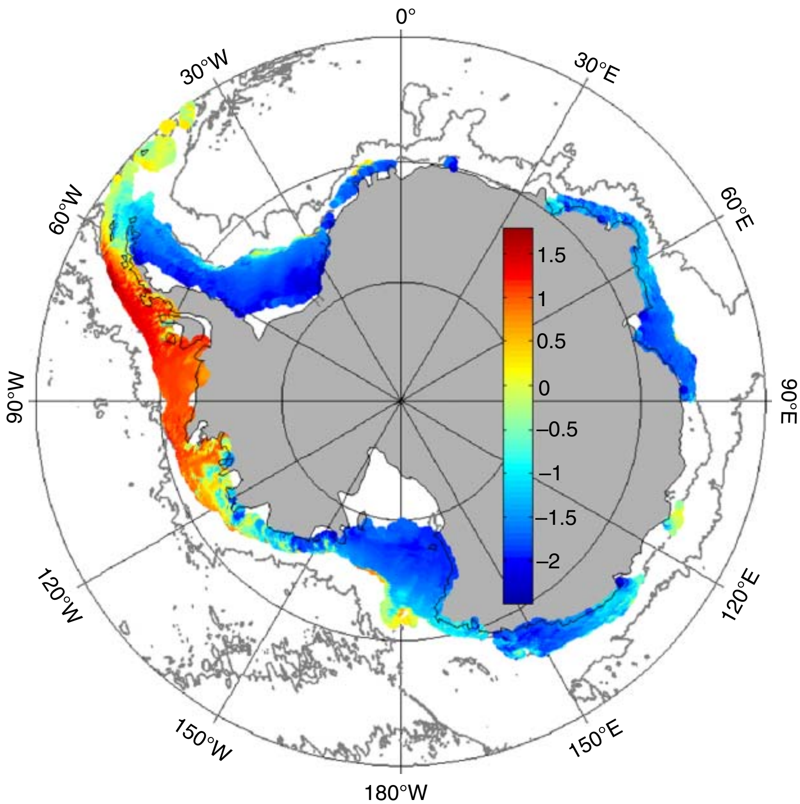


Figure 8.6 Bottom temperatures on the shelf around Antarctica. Note the existence of two primary regimes: a 'warm' sector in west Antarctica (the western Peninsula, Bellingshausen Sea and Amundsen Seas, between 60° and 120°W) and a 'cold' sector around the rest of the continent. The 1000 m and 4000 m depth contours are marked.

these regions, with significant consequences for sea ice production in the different sectors, as detailed below.

The overall water mass structure of the Southern Ocean is most easily comprehended in potential temperature–salinity space (Figure 8.7). The CDW of the ACC is notable for being a warm, saline water mass compared with waters further south. As CDW is the oceanic source for these more southerly waters, this illustrates that it loses heat and becomes freshened overall by air–sea–ice interactions during the transformation process. The upper layer water masses above CDW in the sub-polar region are Antarctic Surface Water (AASW, typically cool and fresh in summer) and winter water (WW, the summertime remnant of the previous winter's mixed layer, characterized by a temperature minimum at around 100 m depth). Filling the layers beneath CDW is Antarctic Bottom Water (AABW), the product of dense shelf water mixing with heavily modified CDW on the shelf and slope regions of Antarctica (Gill, 1973; Whitworth et al., 1998). The shelf waters have high salinity and low temperature, concomitant with their location on the surface melting–freezing line in potential temperature–salinity space (Figure 8.7).

North of the ACC, the upper ocean water mass structure differs greatly from that in the sub-polar region. Above the CDW (and its precursor North Atlantic Deep Water; NADW) lie Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW), formed by deep convection in winter and subduction of cold, fresh WW across the fronts of the ACC (Hanawa & Talley, 2001; McCartney, 1977). These waters are formed in specific sites circumpolarly, and their characteristics vary from basin to basin. AABW permeates the bottom layer here also, as part of its general northward spread in the abyss of the major ocean basins (Johnson, 2008).

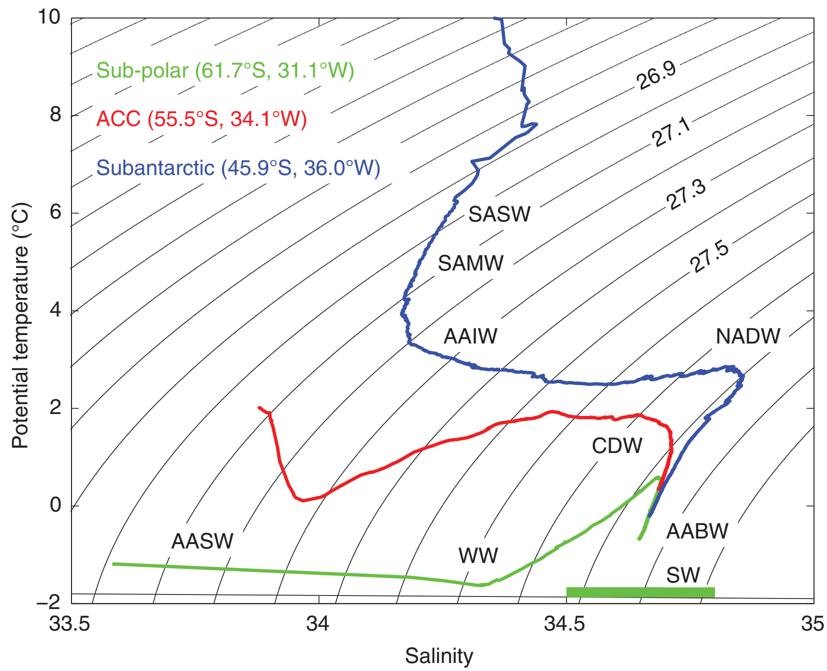


Figure 8.7 Sample profiles from different locations in the Atlantic sector of the Southern Ocean, specifically the Weddell Sea (green), the Antarctic Circumpolar Current (ACC, red) and the subantarctic South Atlantic (blue), in potential temperature–salinity space. Exact positions are as indicated. The melt–freeze line is shown along the bottom of the panel. Different water masses are marked, namely Antarctic Surface Water (AASW), Winter Water (WW), Subantarctic Surface Water (SASW), Antarctic Intermediate Water (AAIW), North Atlantic Deep Water (NADW), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (AABW). The green rectangle denotes the properties of the freezing-point shelf water that provides the dense end member for AABW formation.

It is of particular note that whilst AAIW exists in the subantarctic zone and further north, it is renewed and freshened by upper-layer waters subducting from further south in the ACC (e.g. Naveira Garabato et al., 2009). This is the region where sea ice extent reaches its maximum in winter (Figure 8.4), and hence the upper ocean here is freshened seasonally as this ice melts. The seasonal renewal of AAIW has been demonstrated in the southwest Atlantic sector of the Southern Ocean, with seasonal inflation of the AASW and WW layers causing a pulse of new water to be injected into the AAIW layer (Evans et al., 2014). Precipitation and glacial melt will also contribute to the freshening as they are incorporated into the AASW and WW layers, but nonetheless this illustrates the importance of the sea ice around the Southern Ocean in determining the properties and formation rates of its interior water masses, even at comparatively low latitudes (see also Abernathey et al., 2016; Haumann et al., 2016).

8.3 Sea ice and dense water production in the Southern Ocean

8.3.1 Shelf waters as precursors of AABW

Of the major global water masses that form in the Southern Ocean, one that is notably strongly dependent on sea ice processes is AABW. Key to the formation of AABW is the production of dense waters on the Antarctic shelf, which can then mix and descend down the continental slope to ventilate and renew the ocean abyss (Figure 8.8). This is a very location-specific process, and traditionally it has been the Weddell Sea, Ross Sea and the ocean next to Adélie Land that have been recognized as the major locations where waters are formed that are sufficiently dense to lead to AABW production (Carmack & Foster, 1975; Gill, 1973; Jacobs, 2004).

There has been much renewed interest in AABW formation in recent years, due at least partly to the realization that this water mass is warming and freshening

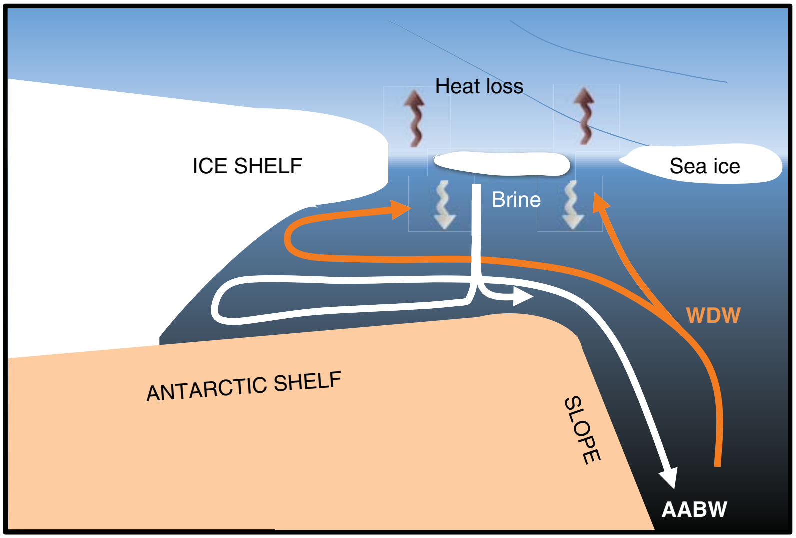


Figure 8.8 Schematic of the processes occurring adjacent to Antarctica that can lead to the production of dense shelf water, and its mixing and cascading to form Antarctic Bottom Water.

across large parts of the Southern Ocean and beyond, with consequences for the global heat budget, sea level rise, benthic biodiversity, and so on (Aoki et al., 2005; Johnson & Doney, 2006; Jullion et al., 2013; Meredith et al., 2008b). The freshening has been largely attributed to the extra injection of glacial melt from the Antarctic continent into the shelf waters that ultimately become incorporated into AABW (Jacobs et al., 2002; Rye et al., 2014), whilst the causes of the warming are still the subject of ongoing research.

The oceanic source for the dense shelf waters and AABW is ultimately CDW, which penetrates southward via the sub-polar gyres, becoming strongly modified en route (Fahrbach et al., 1994). Regionally, this modified water mass is often given a different name to CDW to highlight its modified nature, such as Warm Deep Water (WDW), or Weddell Deep Water in the Weddell Sea. Water from the deep ocean can access the Antarctic shelves in a number of places, with a range of processes (including seasonal wind forcing and fluxes associated with mesoscale eddies) believed to be important (Årthun et al., 2012; Thompson et al., 2014). On the shelf, a variety of shelf water types exist, often being quite fresh (and hence of comparatively low density) due to the input of precipitation and glacial melt. For the conversion of light shelf waters into dense waters, a range of complex processes are important (Figure 8.8), including in some locations the penetration of water beneath the ice shelves that fringe Antarctica as the floating edge of the Antarctic ice sheet (Nicholls et al., 2009). Here, the inflowing water can change its salinity via interactions with the underside of the ice shelf, but it can also be cooled below the surface freezing point, with the pressure to which the water is subject allowing it to remain liquid. This super-cooled shelf water is commonly termed Ice Shelf Water (ISW), and is one of the shelf waters that can be incorporated into the AABW formation process in regions where significant ice shelves exist, such as the Weddell and Ross seas (e.g. Schlosser et al., 1990; Nicholls et al., 2009).

A key process in the densification of the shelf waters prior to their involvement in the production of AABW is the loss of buoyancy to the atmosphere (Renfrew et al., 2002). This is achieved by the loss of heat from shelf waters, which initially cools the waters to the freezing point, after which further heat loss leads to sea ice production. This process is most efficacious in winter, when the difference between ocean and atmosphere temperature is greatest, and once sea ice production commences, brine rejection into the ocean leads to the waters affected becoming progressively denser. In ocean regions with broad shelves, such as the Weddell and Ross seas and Adélie Land, substantial volumes of dense shelf waters can accumulate, having been exposed to sea ice freezing processes for several annual cycles (Jacobs, 2004). There are other regions where significant amounts of dense shelf waters can be produced, even in the absence of a broad shelf region, with the key factor being sufficiently high rates of sea ice production (Ohshima et al., 2013).

It is important to appreciate that, whilst sea ice formation and brine rejection are critical processes in the production of the dense shelf waters that ultimately feed into AABW, the major modification to CDW to become the denser AABW does not take the form of an increase in salinity. This is illustrated clearly in potential temperature – salinity space (Figure 8.7), where it can be seen that AABW is actually fresher than the oceanic source water CDW, and its greater density is due to its much lower temperature. In practice, CDW (in the form of WDW) provides a major source of salt to the Antarctic shelf regions, and dense water production requires loss of heat from these areas, and injection of salt from brine rejection to counter some of the freshening effects of precipitation and glacial melt.

It should also be noted that, whilst significant rates of sea ice production are required to form dense shelf waters and the precursors of AABW, the process of forming sea ice can itself restrict or halt this process, as a complete ice cover would prevent the further loss of ocean heat to the atmosphere. Gaps in the sea ice cover, where the ocean is exposed to the atmosphere even during the winter, are thus critical for the continuous production of sea ice and the creation of significant volumes of dense waters on the Antarctic shelves. Polynyas can be especially effective in this role.

8.3.2 Polynyas

The term polynya is used to denote an enclosed region within an area of ice cover that is persistently or recurrently free from ice, or shows lower ice concentrations than would typically be expected for that area (Chapter 7; Morales-Maqueda et al., 2004). Their sizes vary greatly and they can display significant variability in their occurrence and persistence. In this section, we will describe the importance of polynyas for the production of dense water around Antarctica (further information, and specifics of their importance in the Arctic, is given in Chapter 7).

There are two types of polynyas, namely latent-heat polynyas and sensible-heat polynyas (Figure 8.9). The latter of these are thermally driven, being created from an oceanic sensible heat flux in circumstances

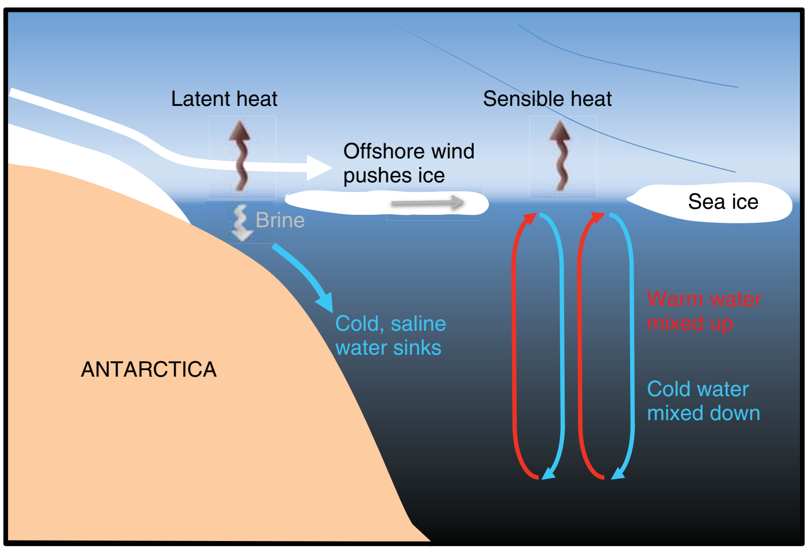


Figure 8.9 Schematic of two polynya types that occur in the Southern Ocean. A sensible-heat polynya is shown on the right, with upwelling of warm water acting to reduce ice production in the locality of the polynya, hence maintaining open water area and permitting heat loss to the atmosphere. A latent-heat polynya is shown on the left, with offshore winds from the Antarctic continent advecting ice away from the coast and maintaining a stretch of open water immediately adjacent to land. The loss of heat via this open water area can enable substantial ice production, brine rejection and the production of dense shelf waters.

where this flux is large enough to melt existing sea ice or restrict the formation of new ice (Martin, 2001). Typically, sensible-heat polynyas are characterized by low sea ice production rates and their dimensions show dependence on the scale of the warm water anomalies responsible for their formation. Upwelling regions can show tendencies to form sensible-heat polynyas, sometimes caused by interactions of ocean currents with submarine features such as seamounts. One example of this is a polynya that can form in the vicinity of Maud Rise, a seamount in the Weddell Sea (Bersch et al., 1992); however, there are comparatively few recurring sensible-heat polynyas in the Southern Ocean.

Of more significance to the production of dense shelf waters around Antarctica are latent-heat polynyas, which fringe the edge of the continent in winter (Kern, 2009). Latent-heat polynyas are mechanically driven, and in general form in the lee of islands, headlands, grounded icebergs and other obstacles that enable export of sea ice by winds or ocean currents without its replacement from upstream in the flow (Martin, 2001). Particularly effective at maintaining coastal latent-heat polynyas in the Antarctic are the katabatic winds, the powerful, gravity-driven flows of air that stream offshore from the continent, advecting the sea ice that has formed and exposing the ocean beneath to further air–sea fluxes and more sea ice production (Morales-Maqueda et al., 2004; Thorsten, 1998).

Surface water in Antarctic latent-heat polynyas is usually maintained at the freezing point during winter, with the huge heat loss to the atmosphere being compensated by the latent heat of fusion associated with new ice formation (Thorsten, 1998). Some polynyas can produce many metres of ice per year, which is very much more productive than the surrounding ice-covered areas. Because of the substantial volumes of sea ice that are produced, these coastal polynyas are often termed ‘ice factories’, and they play a key role in modifying shelf water properties (Thorsten, 1998; Tamura et al., 2008; Ohshima et al., 2013).

The spatial distribution of coastal polynyas around Antarctica is reflected in maps of sea ice production rates (e.g. Figure 8.10; Tamura et al., 2008). The locations of the significant latent-heat polynyas are clear, with associated high rates of ice production in the Ross Sea, Weddell Sea and along the fringes of East Antarctica. High rates of ice production are discernible in the Cape Darnley region, and it was shown recently that this area is a significant site for dense water production, with the water formed spreading around and into the Weddell Sea after descending from the shelf and becoming incorporated into the AABW mixture (Ohshima et al., 2013).

8.3.3 Deep convection in the open Southern Ocean

Whilst dense water formation in the Southern Ocean appears to be presently restricted to the shelf regions, there is evidence that this has not always been the case. In the mid-1970s, a large polynya feature was detected in the pack ice of the open Weddell Sea, some considerable distance from the shelves (Figure 8.11; see also Zwally & Gloersen, 1977). Dubbed the Weddell Polynya, it first appeared in 1974, and reappeared in the following two austral winters (Gordon, 1978).

The Weddell Polynya represented a very significant proportion of the open water area in the Weddell Sea at the times it existed, being around 0.3×10^6 km^2 in size. Consequently, it had the capacity to be a very significant contributor to the net winter heat loss from the ocean to the atmosphere, with consequences for dense water production. Unlike contemporary dense water production adjacent to Antarctica, where the water masses formed convect to the bottom of the shelves at a few hundred metres depth, any sufficiently dense water produced in the open Weddell Sea will be injected directly into the deep and abyssal layers of the ocean, at a few thousand metres depth (Figure 8.3), thus contributing directly to the reservoir of AABW in the world’s ocean. The amount of deep water formed by the Weddell Polynya has been estimated to be approximately 1–3 Sv (Martinson et al., 1981).

The initial cause of the Weddell Polynya and its transience are still subject to some uncertainties, as there is not presently the opportunity to study it in full detail using modern techniques. However, it is believed that sea ice formation in the area was inhibited by ocean convection that injected warm waters from the ocean interior into the surface layer. Other, less persistent polynyas of smaller area have been observed in the vicinity, associated with anomalous upwelling of warm water caused by the interaction of ocean currents with Maud Rise (Bersch et al., 1992; Muench et al., 2001). However, the Weddell Polynya itself has not recurred since 1976.

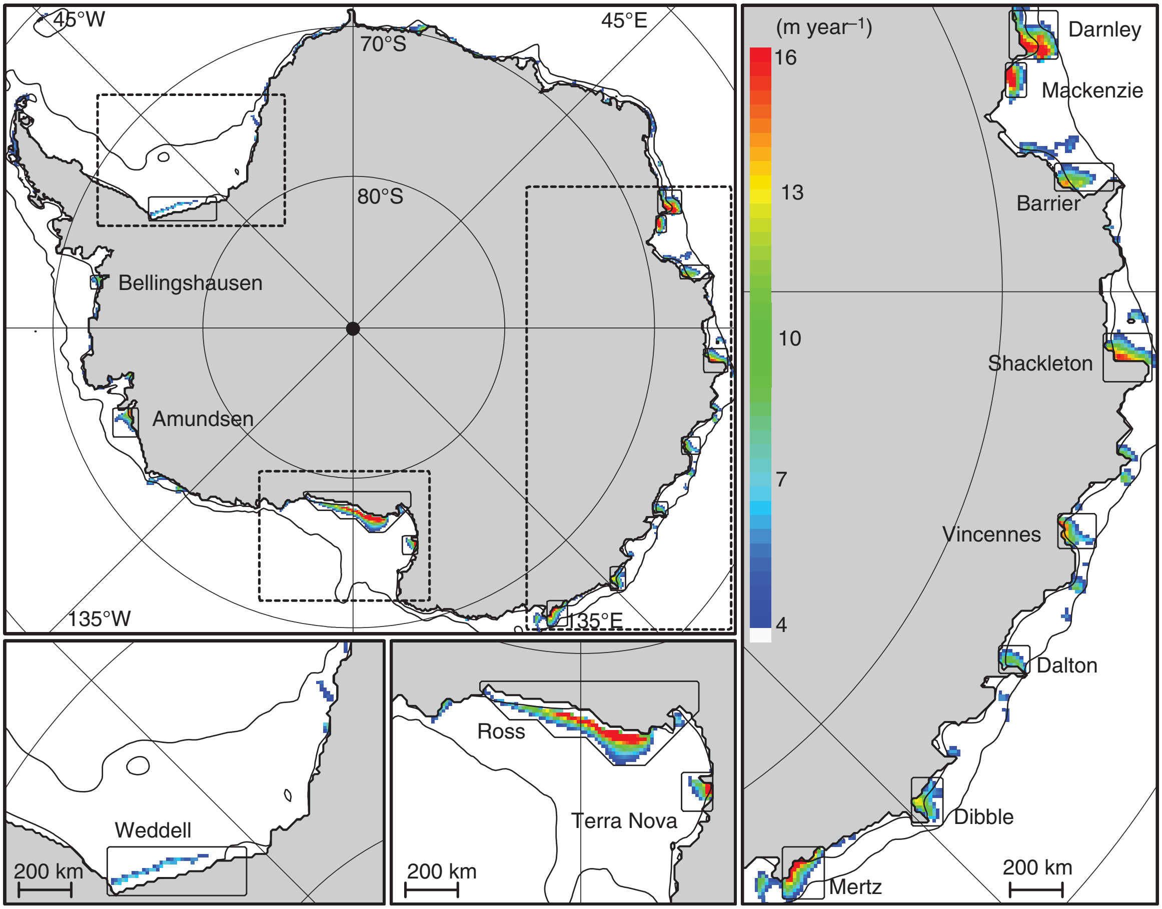


Figure 8.10 Map of annual sea ice production during 1992–2001, estimated from atmospheric reanalysis data. Zoomed panels show sea ice production in the Weddell Sea, Ross Sea and along the coast of East Antarctica. Source: From Tamura et al., 2008. Reproduced with permission from John Wiley & Sons.

There are numerous open and pressing research questions concerning the Weddell Polynya, including what triggered its original formation, what led to its disappearance, and when and how frequently it might recur. Recent investigations have highlighted the importance of the regional hydrological cycle on the stability of the ocean in this area. Ocean density depends predominantly on salinity at cold temperatures, and thus relatively small changes in the amount of freshwater injected to the surface ocean can have significant implications for upper ocean stratification and the propensity for deep convection to occur (Gordon et al., 2007). The hydrological cycle itself depends on a range of climatic factors, including coupled climate modes such as the El Niño-Southern Oscillation (ENSO) phenomenon, and the Southern Annular Mode (SAM; Thompson & Wallace, 2000). These operate at spatial scales from circumpolar to near-global, indicating the sensitivity that polynya activity and dense water production in the Weddell Sea can have to large-scale climatic changes.

Further to this, historical observations and model simulations were used recently to argue that the Weddell Polynya was previously more active than it has been in the satellite era, and that this decline in activity has been caused by human-induced changes in forcing (de Lavergne et al., 2014). These arguments were made on the basis of an observed freshening of the sub-polar Southern Ocean since the 1950s, which has

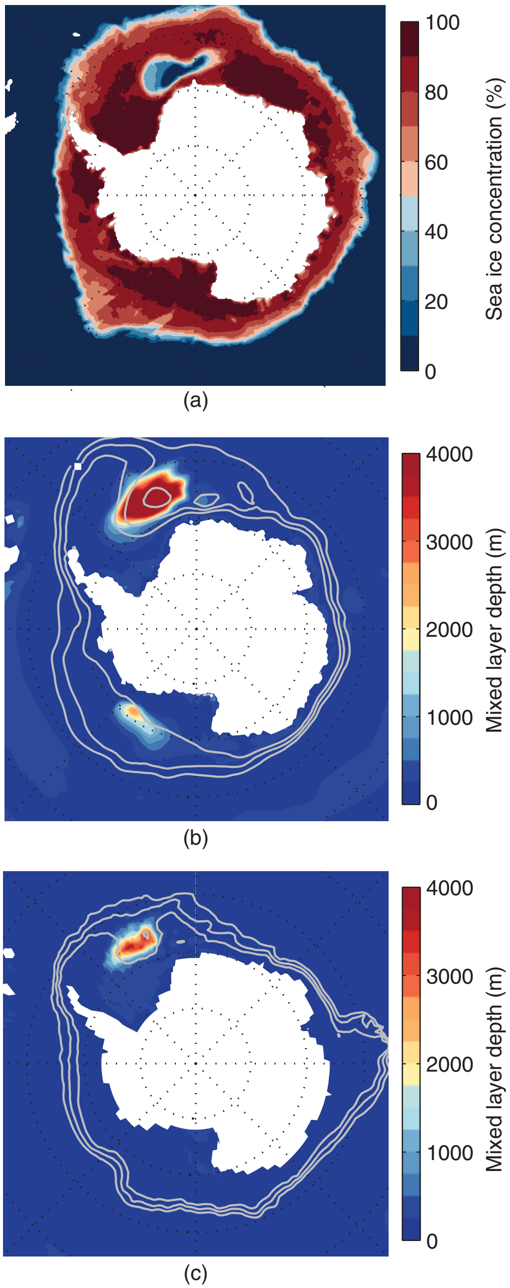


Figure 8.11 (a) Mean September sea ice cover for 1974–1976 from satellite measurements. Note the large polynya within the Weddell Sea pack ice during this period. (b, c) Simulated mixed layer depths using two difference climate models, illustrating the deep-reaching convection that occurred within the polynya. Source: From de Lavergne et al., 2014. Reproduced with permission from Macmillan Publishers Ltd.

increased the strength of the near-surface stratification, thus reducing the tendency for deep convective events to occur. The freshening is believed to derive from two sources, namely stronger precipitation associated with an accelerated hydrological cycle, and increasing injection of meltwater into the ocean from Antarctica's retreating glaciers and ice shelves. Looking forward, both of these processes are thought liable to intensify as anthropogenic climate change progresses, thus indicating that a recurrence of the Weddell Polynya may be less likely in future (de Lavergne et al., 2014), though it should be noted that interannual changes in the freshwater balance of this region associated with coupled climate modes and other natural fluctuations may still lead to conditions in some years where convective activity is possible (Gordon et al., 2007).

8.4 Seasonal cycles of ice and ocean on a 'warm' Antarctic shelf

The previous section outlined how sea ice plays a critical role in the production of the dense waters that feed the AABW layer in the global abyss. The shelf processes outlined occur exclusively in the 'cold' sector of Antarctica (Figure 8.6), but it would be misleading to imply that sea ice does not play a major role in influencing the ocean in the 'warm' (Amundsen/Bellingshausen Sea) sector also. Indeed, it is one of the most significant factors in controlling ocean circulation and properties here, and feedbacks from the ocean to the ice are very important in determining the nature and behaviour of the ice cover in this region (Stammerjohn et al., 2003; Venables & Meredith, 2014).

In this context, a great deal of useful information has been obtained from the western Antarctic Peninsula (wAP). This is the most accessible part of Antarctica, and hence has the greatest concentration of manned research stations. Their presence, combined with close proximity to the ocean, means that oceanographic and sea ice data can be collected here even during the winter months. Further, the wAP is of great scientific interest because it recently warmed more rapidly than any other region of the southern hemisphere, with annual-mean atmospheric temperatures at wAP research stations increasing by an average of $3.7 \pm 1.6°C\ century^{-1}$ during the second half of the 20th century (Smith et al., 1996; Vaughan et al., 2003).

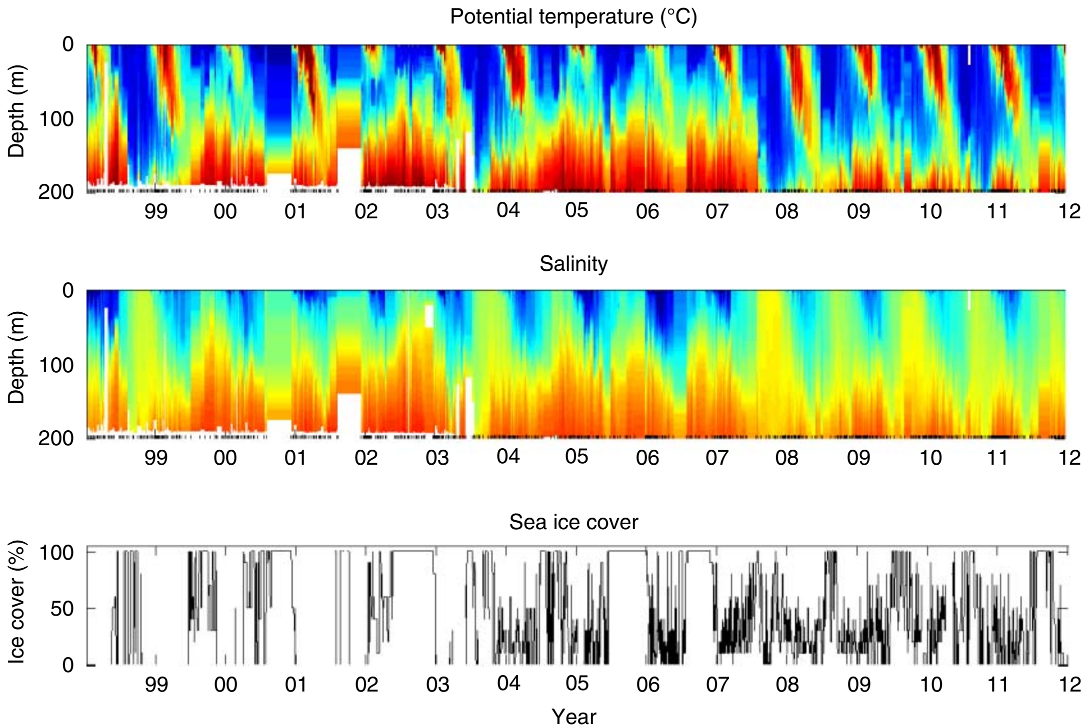


Figure 8.12 Sequences of upper-ocean potential temperature (upper panel) and salinity (middle panel) from the Rothera Time Series (RaTS) at the western Antarctic Peninsula. Note, in particular, the strong seasonality in both series, with interannual changes superposed, each of which is strongly coupled to shifts in the sea ice (lower panel).

Surface ocean temperatures at the wAP rose by more than 1°C during this same period (Meredith & King, 2005), with a concordant retreat of the majority of glaciers and an acceleration in their retreat rates (Cook et al., 2005). The causes of this rapid climatic change are not fully determined, but a wind-induced increase in the flow of CDW from the ACC onto the shelf has been implicated in a number of the changes observed (Martinson, 2011).

Many examples of progress in understanding the ocean–ice system at the wAP exist (e.g. Massom et al., 2008; Stammerjohn et al., 2008a; Turner et al., 2013), but here we present an illustrative case from a long, year-round time series in the nearshore waters on the Peninsula shelf. This dataset was collected adjacent to Rothera Research Station, approximately midway along the western side of the Antarctic Peninsula, and is appropriately called the Rothera Time Series (RaTS) (Clarke et al., 2008). This series includes full oceanographic data from all seasons, and as such is almost unique in the Antarctic context.

Strong seasonality in the upper ocean at the ice-influenced wAP is clearly visible in the data collected (Figure 8.12). The summer periods, with ocean temperatures above 0°C, are comparatively short, and interspersed with significantly longer periods during which the near-surface ocean is close to the freezing point (Figure 8.12; upper panel). This is a consequence of the energy budget of the ocean–sea ice system here, with significant thermal energy in early spring utilized to melt the residual sea ice from the previous winter, rather than warming the seawater; consequently the water temperature remains comparatively low during summer and rapidly reduces to freezing in autumn.

Salinity shows the same significant seasonality, with much fresher waters during spring and summer, interspersed with more saline upper-ocean characteristics during winter (Figure 8.12; middle panel). The phasing of this seasonality is closely tied to the seasonality of the sea ice itself, which exerts a strong, direct influence on ocean salinity (lower panel). This is most clearly manifested by the shift toward more saline water after

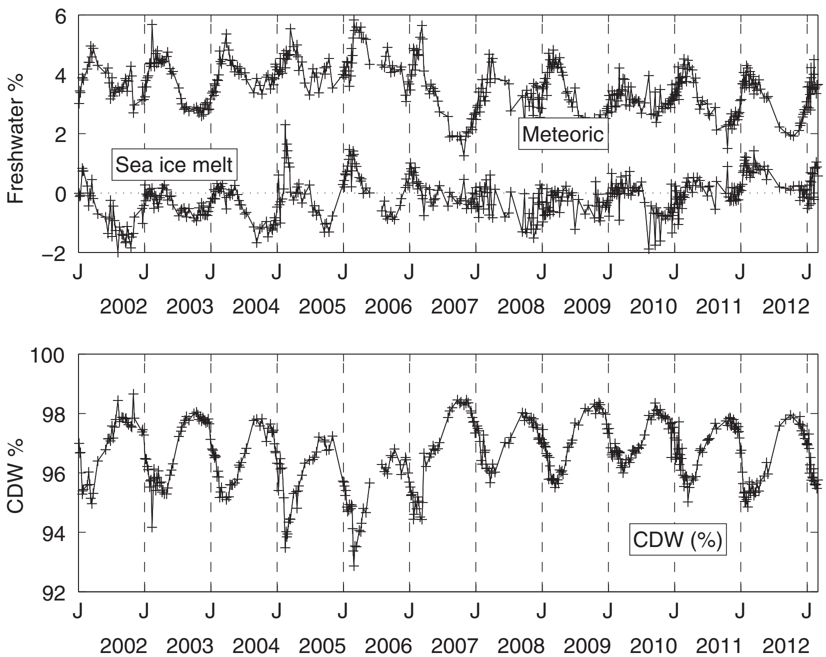


Figure 8.13 Sequences of sea ice melt and meteoric water (glacial discharge plus precipitation) at the western Antarctic Peninsula, as quantified in the near-surface ocean at Rothera Time Series (RaTS) using salinity and oxygen isotope data. Note that the sea ice melt contribution can be both positive and negative; this reflects the fact that sea ice can both melt into and form from seawater, whereas meteoric inputs can only freshen the seawater. Lower panel represents the contribution of saline Circumpolar Deep Water (CDW) to the overall budget. Note the strong seasonality in both freshwater components, and the general dominance of meteoric water over sea ice melt. Source: adapted from Meredith et al., 2013b.

the end of summer, which is caused by the sea ice production, mixed layer deepening and the entrainment of saline CDW from below. The consequent melt of this sea ice contributes to the subsequent freshening in spring and summer, but it is not the only contributor; other terms in the freshwater budget, such as glacial discharge and precipitation, are also important.

This can be illustrated more clearly, and the impact of sea ice on changing ocean salinity demonstrated more directly, by using other oceanographic freshwater tracers in addition to salinity. One very useful such tracer is the ratio of stable isotopes of oxygen in seawater, termed $\delta^{18}O$. The great utility of this ocean tracer is that, when measured alongside salinity, it allows the freshwater supplied to the ocean from sea ice melt to be quantified separately from that supplied by meteoric sources (here meaning the collective input from glaciers and precipitation) (Craig & Gordon, 1965).

When this technique is applied to water samples collected near the surface at Rothera, the seasonality in both the sea ice melt and meteoric freshwater is very clear (Figure 8.13; Meredith et al., 2008a, 2010). Interestingly, the seasonal signals are broadly comparable between the sea ice cycle and meteoric water cycle (about 2–3%, peak-to-peak), despite the growth and decay of sea ice around Antarctica often being conceived as the most significant seasonal signal on the planet. It is clear that, in this locality, other sources of freshwater contribute just as much to the seasonality in the oceanic freshwater budget.

It should be noted also that the meteoric freshwater term is always higher than the sea ice melt term. This is a consequence of the combined effect of glacial discharge and snow in the nearshore environment being dominant over the sea ice inputs. At other locations, further from the glacial sources and away from the orographically induced increases in precipitation caused by the Antarctic Peninsula mountains, the balance is likely to be different.

In the time series plots of freshwater contributions at Rothera (Figure 8.13), and in the sequence of hydrographic profiles (Figure 8.12), it is clear that there are some longer-term (interannual) changes in addition to the seasonal cycles. Some of the interannual changes relate to anomalous forcings associated with ENSO and the SAM, which are the major modes of coupled climatic variability that impact this part of the Southern Ocean (Stammerjohn et al., 2008b). Examples of this impact include the deep upper-ocean mixed layers observed in 1998, 2003 and 2010 (Figure 8.12), when anomalous atmospheric forcings led to perturbations in the sea ice field, and consequently modified the upper-ocean response. In particular, years with reduced sea ice coverage in winter (Figure 8.12; lower panel) are known to lead to deeper mixed layers, due to the combination of greater wind-induced upper ocean mixing and increased buoyancy loss. This reduced stratification can persist through to the following spring, creating feedbacks in the system via exchanges of heat between the atmosphere and ocean (Venables & Meredith, 2014), and with an impact on biological productivity (Venables et al., 2013).

There are also some manifestations of decadal variability in the data, including a decline in meteoric water prevalence (Figure 8.13), decreasing seasonality in the sea ice concentrations (Figure 8.13), and a progressive shift towards warmer and more saline upper ocean characteristics, with deeper mixed layers in winter (Figure 8.12). Whilst decadal variability cannot be not fully resolved in series of this length, these signals are known to be manifestations of longer-period climatic changes ongoing at the Antarctic Peninsula.

The very significant atmospheric warming that occurred recently at the Peninsula was commensurate with a rapid retreat of the sea ice (Stammerjohn et al., 2012; Turner et al., 2013). However, it is known that such changes in the sea ice field were not just a passive consequence of the atmospheric warming, but instead they played an active role in sustaining and accelerating the warming trend itself (Meredith & King, 2005). In practice, the ocean–ice–atmosphere system in this area of Antarctica was moved from one where relatively strong ice production in autumn and winter was balanced by relatively strong melt in spring and summer, to one with much weaker manifestations of these processes, and the role of the upper ocean and sea ice was to act as a positive feedback on this transition (Meredith & King, 2005). It is thus possible that if an atmospheric warming trend resumes at the Peninsula, the area will move from a predominantly Antarctic climate to a subantarctic one, becoming progressively free of sea ice in due course. The role of external forcings is already known to be significant (Stammerjohn et al., 2008b; Li et al., 2014;), and more research that reliably incorporates regional and global scales is needed to improve predictive skill in this regard.

8.5 The future

The Southern Ocean is disproportionately important in the functioning of the Earth system, being the prime location where deep waters in the global ocean are upwelled to the surface and converted into other water masses that sink and replenish the different limbs of the global ocean overturning circulation. It is a major regulator of planetary climate, it acts as a significant sink for anthropogenic carbon dioxide from the atmosphere, and it plays a strong role in controlling deglaciation of the Antarctic continent, with implications for sea level rise. It is also home to a unique ecosystem, within which some species are commercially exploited. Sea ice in the Southern Ocean influences each of these globally important functions, and understanding how the interactions of the ocean and ice occur is a high scientific priority.

Despite the importance attached to understanding the interactions of sea ice with the Southern Ocean, there is still a very great deal that remains undetermined. In no small part, this is due to the presence of sea ice itself, which presents a major obstacle to conventional (ship-based) fieldwork, creating significant difficulties in obtaining the coherent, sustained datasets that are vital in developing the process-based understanding and in testing model constructs. This difficulty is most challenging in winter, when the Southern Ocean is one of the harshest environments on the planet in which to conduct fieldwork, but nonetheless the winter season is when some of the key processes occur that make the Southern Ocean profoundly important on the planetary scale.

Ocean science has developed dramatically since the days when it was predominantly reliant on research vessels for data gathering, and this has opened up many opportunities to find solutions to the conundrum of how

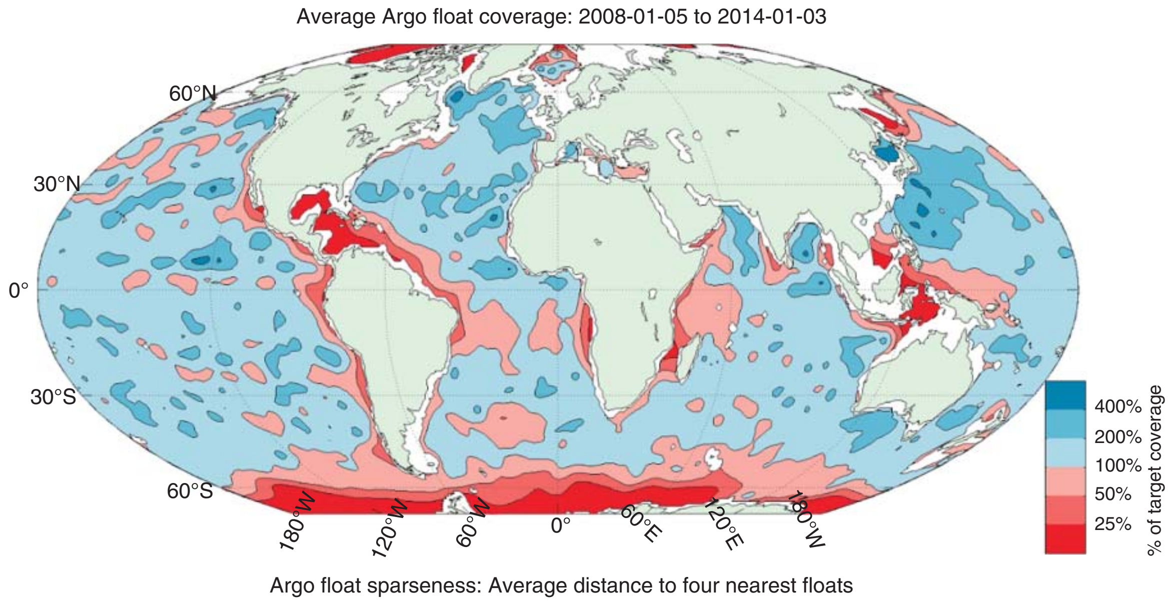


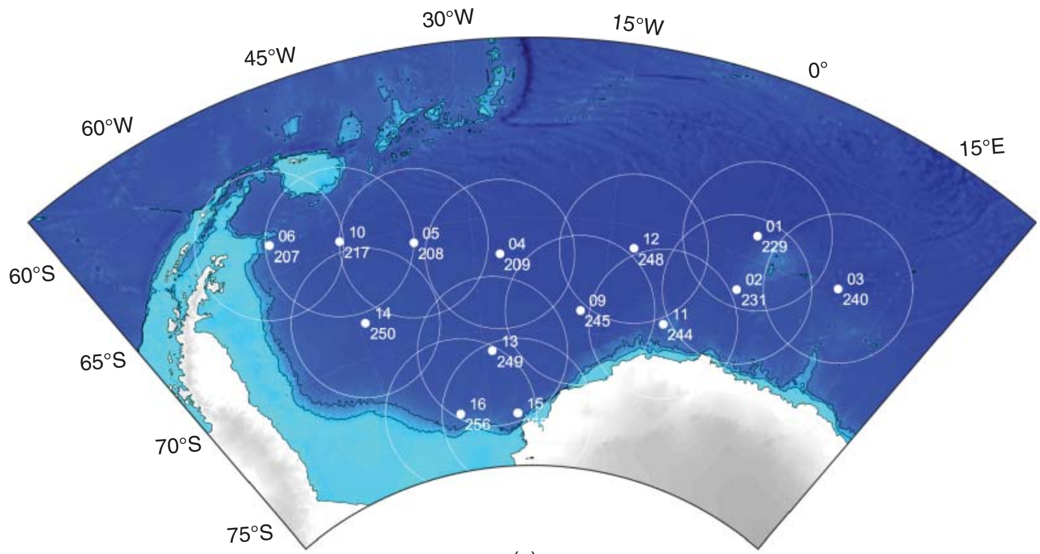
Figure 8.14 Distribution of Argo float coverage in the global ocean, for the period 2008 to 2014. Note the decline in coverage in major parts of the Southern Ocean, especially those typically covered by sea ice. Source: courtesy of JCOMMOPS/Argo.

to obtain sustained, systematic ocean data in the sea ice zone. One example of a technological development that has revolutionized ocean science is the development of the profiling float, which drifts passively at a prescribed 'parking depth' (typically 1000 m), and at intervals sinks then rises to the surface, collecting oceanographic data as it cycles. These data are transmitted to land stations by satellite when the float is at the surface. A network of more than 3000 such floats, called Argo, now exists in the world's oceans, providing real-time data on the upper 2000 m (Figure 8.14).

The Argo array has enabled many radical new insights into the functioning of the ocean within the global climate system, not least in accurately quantifying the oceanic uptake of heat due to global warming (currently > 93% of the total extra heat in the Earth system). The distribution of Argo floats in the Southern Ocean is now very creditable in the predominantly ice-free regions (Figure 8.14); however, it declines markedly once the more ice-influenced areas are encountered. This is a consequence of the physical hazard that the ice presents to the float, damaging the float on impact as it ascends or crushing it while it is at the surface.

Various techniques have been developed to alleviate this issue, including equipping floats with ice-detection algorithms that enable them to estimate whether an ascent is likely to be impeded by sea ice at the surface and to abort any ascent accordingly (Klatt et al., 2007). When floats are unable to surface, they can record oceanographic data, but cannot obtain positional fixes via satellite. One ambitious project has circumvented this problem by deploying a network of sound sources in the Weddell Sea, and tracking the floats via underwater acoustics (Figure 8.15). These developments and other ongoing developments that include equipping the floats with biogeochemical sensors and extending their depth range will ensure the continued provision of vital data from the sub-sea-ice regions into the future.

Profiling floats are just one example of the innovative technology being used to better understand sea ice–ocean interactions around Antarctica. A further example is the equipping of marine mammals with miniaturized oceanographic sensors, which record profiles of ocean properties when the animal dives, and relay the data to land via satellite when the animal surfaces. Such sensors have been deployed widely on species such as elephant seals in the Southern Ocean; these can range for huge distances (thousands of km) and dive to great depths (down to ~1500 m), thus providing vast quantities of data that complement the



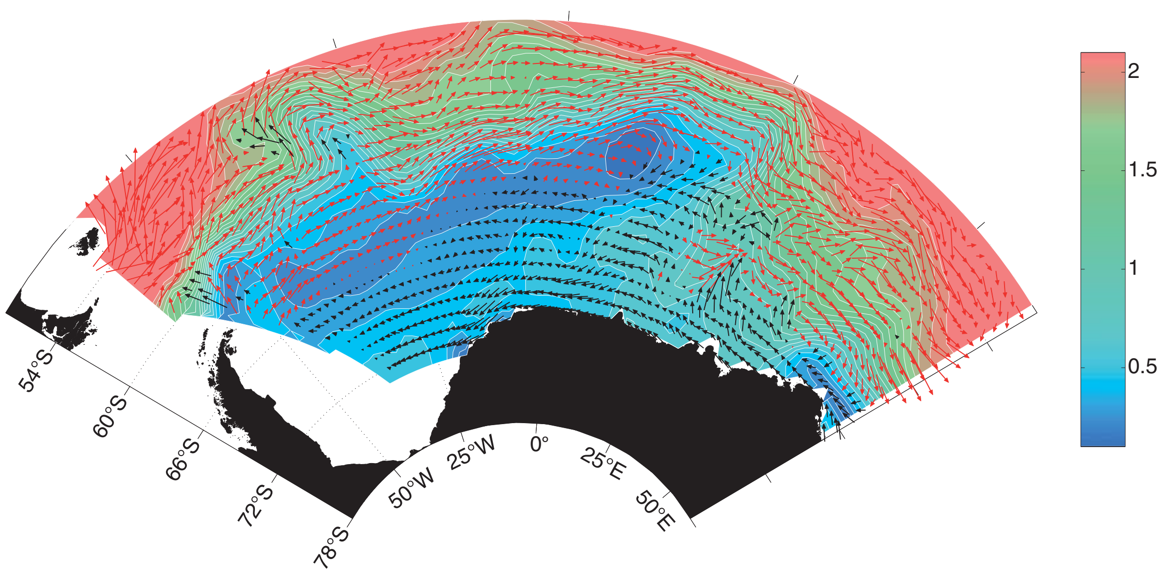
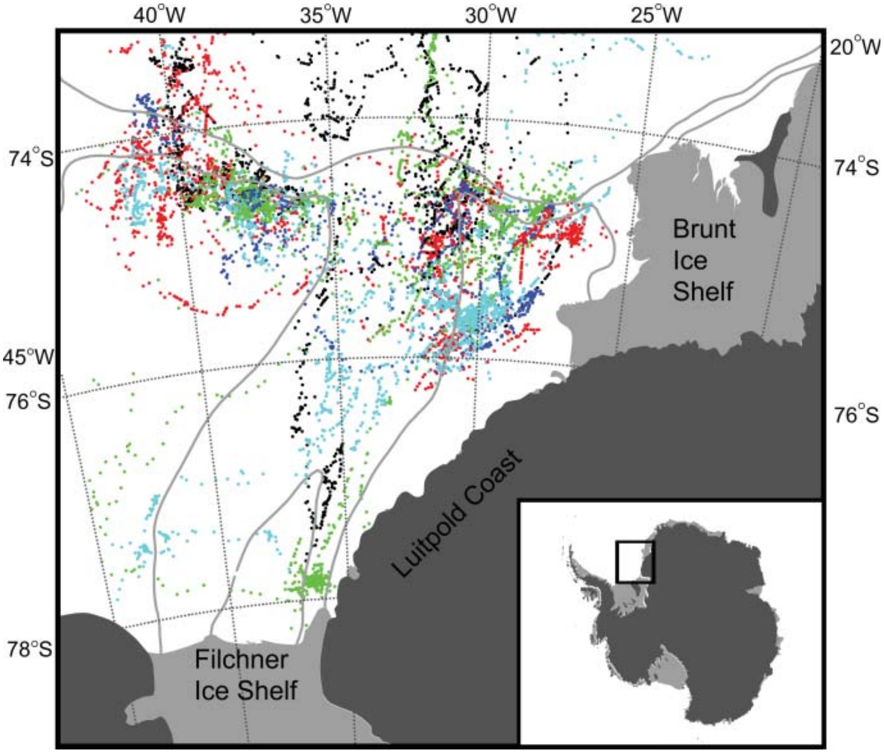


Figure 8.15 (a) The array of sound source moorings deployed by the Alfred Wegener Institute (AWI) in the Weddell Sea for tracking under-ice profiling floats (white circles denoting the area ensonified by each mooring); (b) map of the circulation and temperature at the drift depth of the floats from the data obtained. Source: Figures courtesy of Olaf Boebel and Olaf Klatt, AWI.

Argo float datasets (e.g. Boehme et al., 2008). The integrated Argo and seal datasets have been used to provide unprecedented detail on frontal structures in the Southern Ocean, and also to calculate sea ice production rates deep within the pack (Charrassin et al., 2008). Because the data are collected wherever the seals swim and forage, they are also inherently interdisciplinary and valuable for studies of animal behaviour and ecology as well as oceanography and ocean climate (Biuw et al., 2007).

(a)



(b)

Figure 8.16 (a) A Weddell seal tagged with a miniaturized oceanographic sensor unit (photograph courtesy of Capt. Ralph Stevens); (b) spatial distribution of ocean profiles obtained from seals similarly tagged in 2011. Source: map by Keith Nicholls, adapted from Årthun et al., 2012 with permission; see also Årthun et al., 2012 and Nicholls et al., 2008.

In the context of sea ice, the great utility of this technique is that certain animal species venture into and exploit sea ice around Antarctica, including in areas from which it is extremely difficult or impossible to collect oceanographic data via other means. For example, Weddell seals differ from other seal species in that they do not move northwards in autumn and winter as the sea ice edge advances, but remain at high southern latitudes year-round, retaining vital access to the ocean by continually gnawing at holes in the ice to keep them open. Weddell seals tagged with miniaturized oceanographic sensors have produced some unique data that have given significant new insights into the wintertime interactions of ocean and sea ice in this region of the Southern Ocean (Nicholls et al., 2008; Figure 8.16).

Other techniques are continually being developed to help alleviate the dearth of data from the ice-infested regions of the Southern Ocean. Recent developments include ocean gliders, which are autonomous,

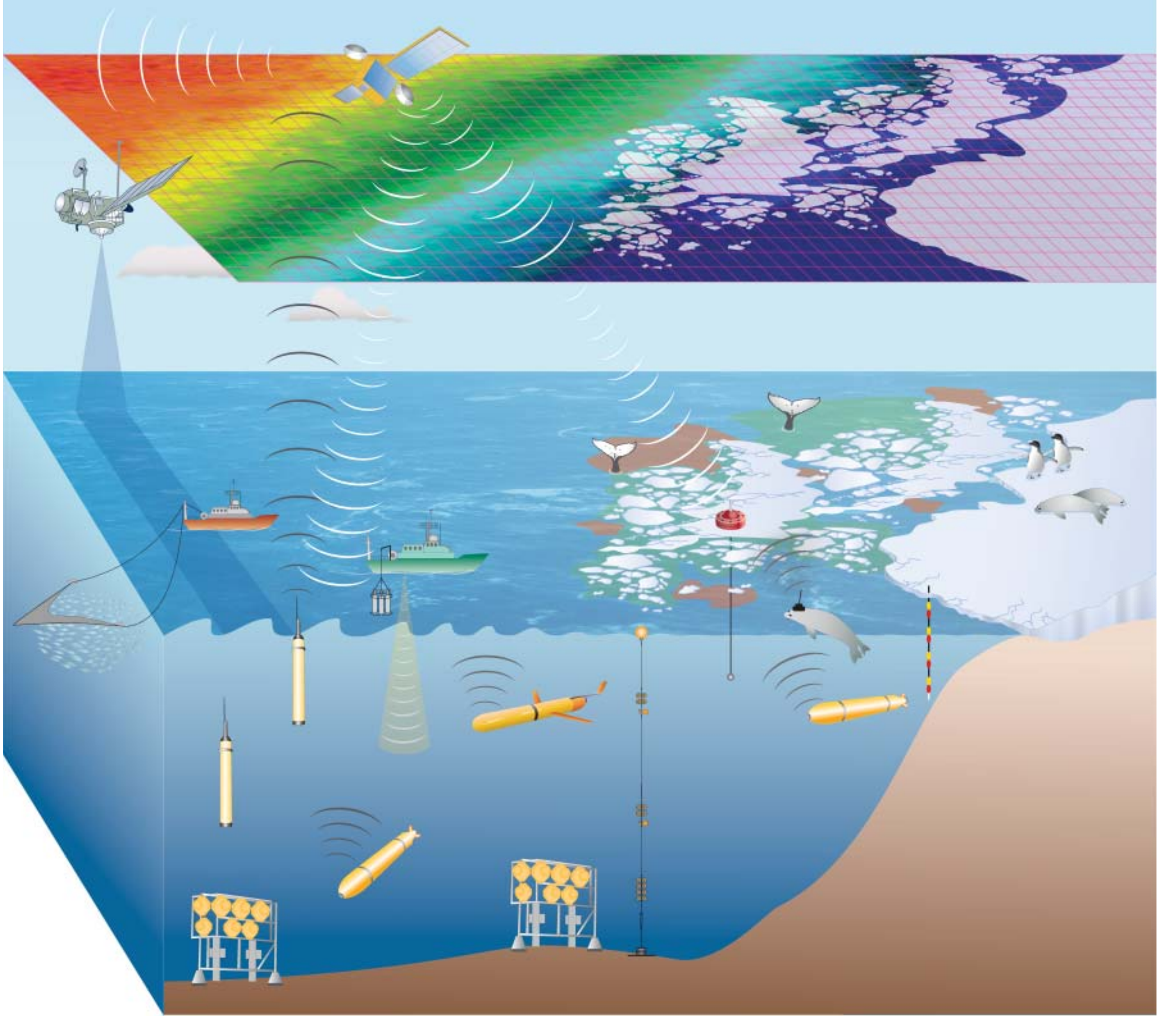


Figure 8.17 Schematic of a cyber-infrastructure-based Southern Ocean Observing System (SOOS), incorporating both autonomous and conventional platforms, but relying progressively more on the former over time. Source: Meredith et al., 2013. Reproduced with permission from Elsevier.

buoyancy-driven vehicles that can survey the upper 1000 m of the water column over large distances and long periods, with deployments of up to several months now possible. In the Arctic, deployments of such ocean gliders beneath the sea ice have been carried out, with navigation and control being made possible via an acoustic communications network. This offers great potential in the Southern Ocean also, for missions both beneath the perennial sea ice in summer and under the full pack ice in winter. Powered unmanned vehicles can deliver oceanographic data from beneath sea ice, and whilst their duration is typically much less than that of an ocean glider, this technology still promises to be a vital contribution to sustained data gathering efforts in the future.

Despite these technological advances, it seems likely that the Southern Ocean will be data-sparse compared with the rest of the world's oceans for some time to come, with the ice-covered regions of the Southern Ocean being the most affected. It thus behooves us to challenge ourselves to find the optimal combination of investments (ships, moorings, autonomous vehicles, satellite sensors, etc.) to produce the sustained data streams from the Southern Ocean that are required to address the most significant scientific challenges. To achieve this, an international initiative, the Southern Ocean Observing System (SOOS), has developed a strategy for how sustained ocean observations in this region should be coordinated and conducted into the future, including a specific focus on sea ice and the sub-ice areas of the ocean (Figure 8.17; Meredith et al., 2013a). Achieving this vision of a fully capable, sustained, integrated observing system that can function even in winter under some of the harshest conditions on the planet will not be trivial, but the scientific advances to be achieved, and the societal importance of those advances, dictate that it should be a high international priority.

8.6 Acknowledgements

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