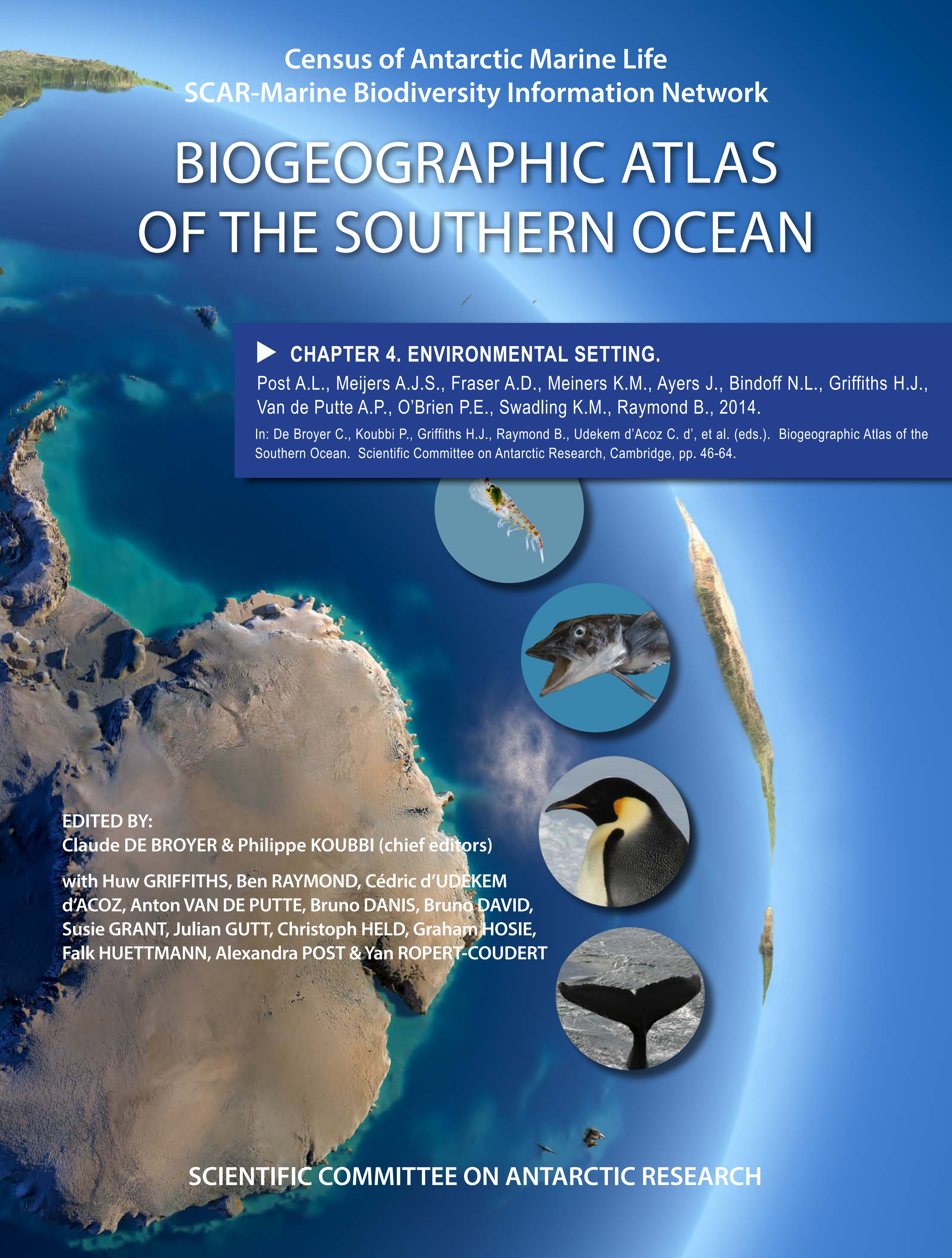

Census of Antarctic Marine Life
SCAR-Marine Biodiversity Information Network

BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

▶ CHAPTER 4. ENVIRONMENTAL SETTING.

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

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4. Environmental Setting

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1. Introduction

Despite the success of the Census of Antarctic Marine Life in advancing our knowledge and awareness of the Antarctic marine biota, there are still many gaps in our understanding of distributional patterns. The Southern Ocean is huge in its geographic scope and collecting and classifying biological specimens is both time-consuming and expensive. The distributions of benthic and pelagic organisms around the Antarctic margin and in the Southern Ocean are influenced by a wide range of factors, including physical and chemical environmental drivers. Many physical datasets can be collected relatively cheaply and rapidly across broad geographic scales, allowing a detailed picture of the physical environment to be developed. By understanding the way in which environmental parameters influence the distribution and diversity of the marine biota, bio-physical models can be developed to better predict and model their distribution.

In this atlas, we present a synthesis of relevant environmental factors, which could be incorporated in bio-physical models in future work. The factors included are the depth and gradient of the seafloor, geomorphic features, bottom sediments, the locations of potential shelf refugia during the last glaciation, sea ice extent and seasonality, physical oceanographic processes and the distribution of nutrients and oxygen at the sea surface and through the water column. These environmental factors are discussed in this chapter, along with their broad relevance implications for biodiversity patterns.

2. Bathymetry and slope

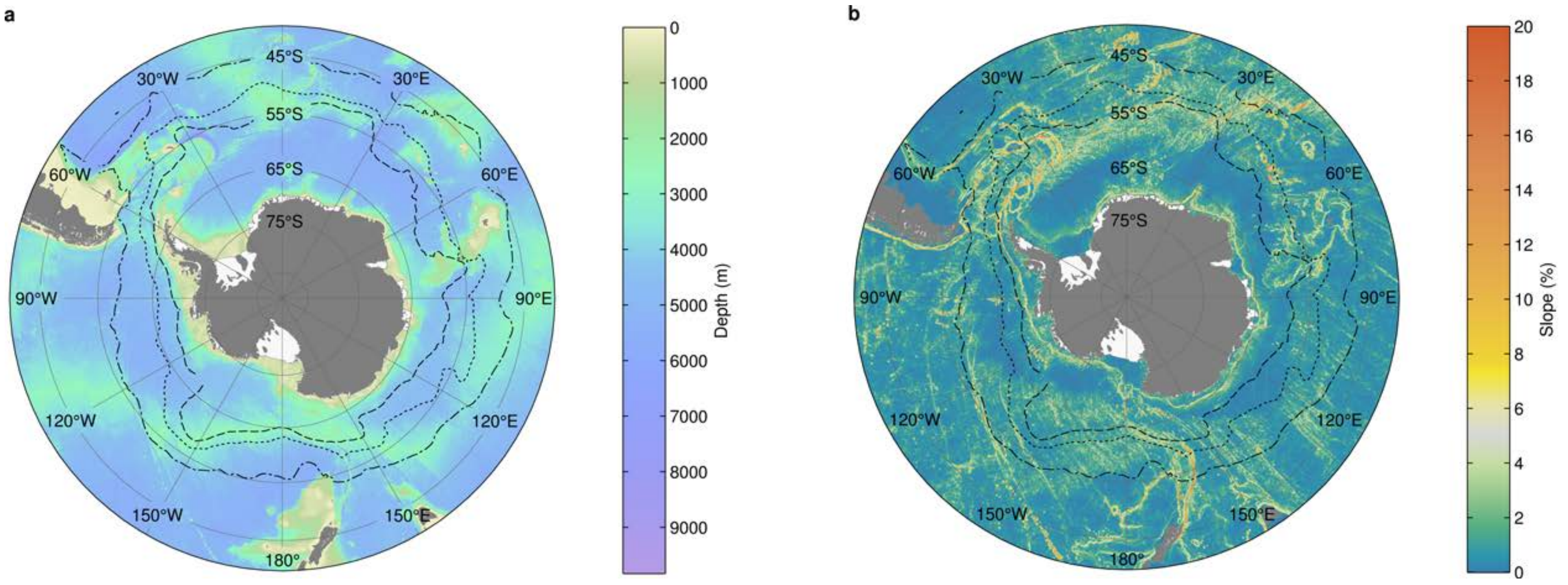
The Southern Ocean is comprised of three ocean basins: the Pacific, the Indian and the Atlantic (see Map 1 in chapter 1). These basins exceed 3000 m in depth, and are separated by submarine ridges, plateaus, and in the case of the Atlantic and Pacific basins, the island chain of the Scotia Arc. Around the Antarctic margin the continental shelf is unusually deep, averaging 450 m, and exceeding 1000 m in places (Clarke & Johnston 2003). The depth of the shelf largely reflects over-deepening of inner-shelf basins by glacial erosion, as well as depression of the crust by isostatic loading during ice sheet expansion. The shelf break, defined by the change in gradient, occurs at depths ranging from 200–1000 m, depending on the orientation of glacial basins and the adjacent shallow banks (Map 1). Detailed measurements of the upper slope on the East Antarctic margin indicate slope gradients of between 2 and >10% (Stagg *et al.* 2004). The transition to the lower slope is marked by a reduction in gradient to 0.7–1.75%. The shelf width varies considerably. Large glacial embayments, such as in the Ross and Weddell Seas, form shelf seas spanning up to 1000 km from the continental margin to the shelf edge, and are largely covered by floating ice shelves. The narrowest parts of the shelf occur off Dronning Maud Land, which has a shelf width of as little as 15 km in places.

The Southern Ocean contains fewer depth-restricted species than other ocean basins (Brey *et al.* 1996), most likely due to the over-deepening of shelf environments and the periodic glaciations which largely eliminated shelf habitats. Despite this, water depth has been shown to be a strong delimiter of biological communities in various settings around the Antarctic margin. Water depth shows a strong correlation with the distribution of demersal fish and benthic communities on the George V shelf and slope (Beaman & Harris 2005, Koubbi *et al.* 2010, Post *et al.* 2010, Post *et al.* 2011), and benthic communities in the Ross Sea (Barry *et al.* 2003) and the Weddell and Lazarev Seas (Gutt & Starmans 1998). Water depth can be linked to the strength of bottom currents, and hence deposition of organic matter (e.g. as shown for the Ross, Weddell and Lazarev Seas), and on the Antarctic margin also reflects long-term sedimentation patterns established following previous glaciations. Deep basins formed by the expansion of glaciers towards the shelf edge during past glacial periods now act as depocenters for the accumulation of fine-grained siliceous mud and ooze sourced from the productive shelf waters (e.g. Harris *et al.* 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile icesheet around these broad features. Depth on the shelf also largely defines the impact of iceberg scouring, with icebergs commonly grounding and scouring the seafloor to depths of up to 500 m (Barnes & Lien 1988, Dowdeswell & Bamber 2007).

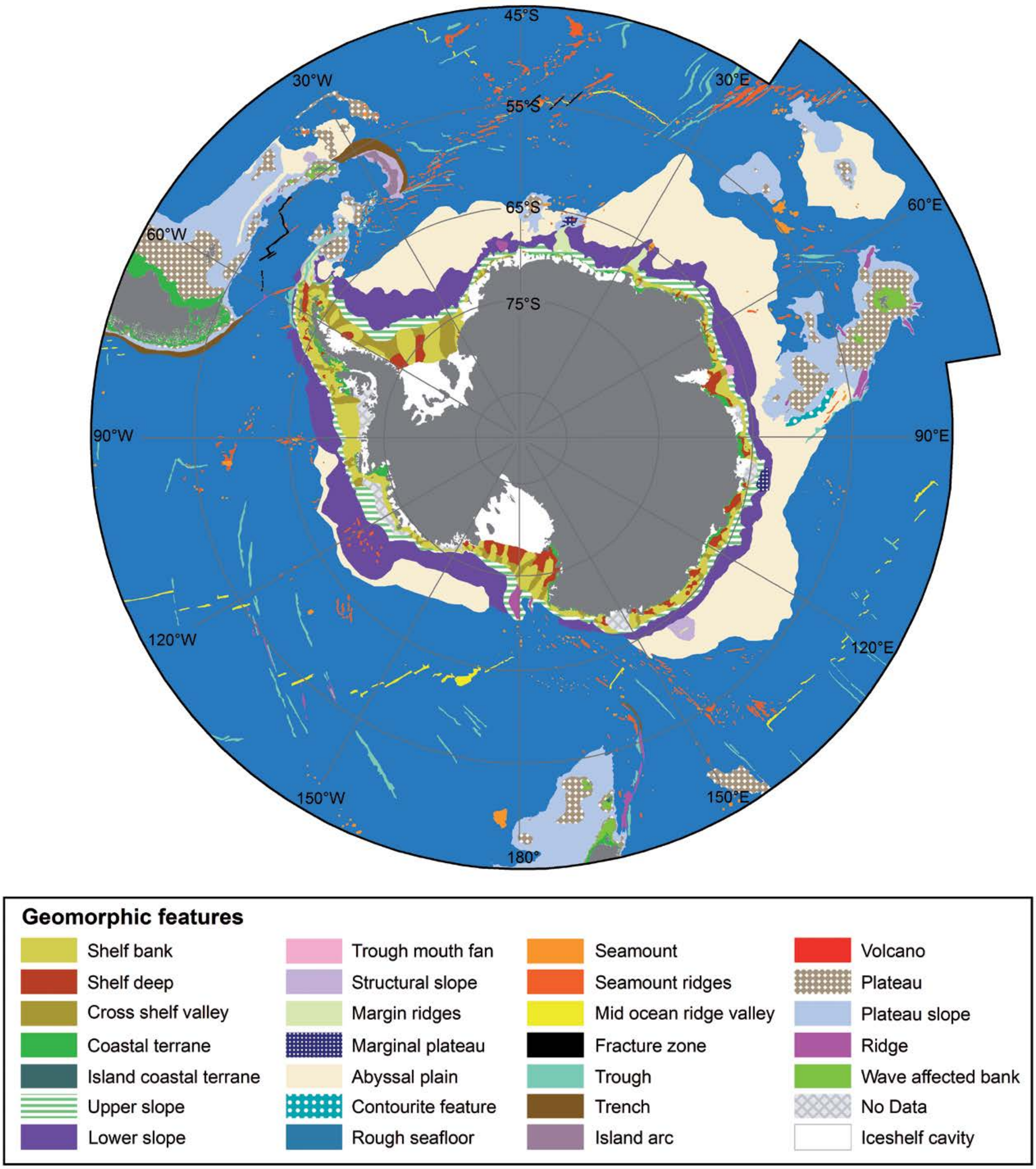
3. Geomorphology

Depth alone does not describe the seafloor environment from a habitat perspective. For example, deep basins on the shelf, which can extend to depths greater than 1000 m, are very different environments to regions of similar depth on the continental slope. Deep shelf basins often contain thick accumulations of muddy biogenic material produced in the shelf surface waters (Domack 1982, Beaman & Harris 2005), while similar depths on the slope are often energetic, current-swept environments and deeply incised by canyons (see O'Brien *et al.* 2009). The distinction between deep shelf basins and shelf banks can also delineate between communities affected by iceberg scouring, with the basins typically too deep to be affected by iceberg disturbance (Barnes & Lien 1988, Dowdeswell & Bamber 2007).

Geomorphic features delineate distinct sedimentary and oceanographic environments that can be related to major habitat characteristics. Such characteristics include sea floor type (hard versus soft substrate), ice keel scouring, sediment deposition or erosion and current regimes. On the Antarctic shelf, geomorphic features have been shown to provide an effective



Environmental Setting Map 1 (a) Bathymetry derived from satellite altimetry and ship depth soundings (Smith & Sandwell 1997); (b) slope calculated from the same data. The dashed line shows the Southern Antarctic Circumpolar Current Front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).



Environmental Setting Map 2 Geomorphic features of the Southern Ocean (expanded from O'Brien *et al.* 2009). See Table 1 for definition of the geomorphic features.

guide to the broad-scale distribution of benthic communities (Barry *et al.* 2003, Beaman & Harris 2005, Koubbi *et al.* 2010, Post *et al.* 2010, Post *et al.* 2011). The distribution of core shelf communities, as defined by Gutt (2007), can also be broadly approximated by shelf geomorphology and oceanography, with communities such as mobile deposit feeders and infaunal communities confined to areas where modern fine sediment can accumulate, such as shelf depressions. Seamounts are another feature that have been shown to be biologically significant, supporting rich benthic communities with a high number of endemic species (Richer de Forges *et al.* 2000). Other features which potentially provide unusual substrates and modify local ocean currents, such as marginal ridges and plateaus, may similarly support distinct and diverse benthic communities.

Map 2 shows geomorphic units mapped for the Southern Ocean south of 45ºS, with expansion to 40ºS in the region of the Del Cano Rise (O'Brien *et al.* 2009, A. Post unpublished data). Broad-scale mapping of the New Zealand and South American margins was included, but is not intended to replace detailed schemes produced for these regions. Geomorphic units were digitised by hand as polygons in ArcGIS, based on bathymetric data and using the criteria shown in Table 1 (for more details see O'Brien *et al.* 2009). The key datasets used were the GEBCO08 bathymetry contours, which are derived from ship track data, and the ETOPO2 satellite bathymetry (Smith & Sandwell 1997). Based on interpretation of the seafloor bathymetry, 28 geomorphic units were identified at a scale of about 1: 1–2 million (Map 2). In this classification, the International Hydrographic Organisation (2001) classification of undersea features was used as a starting point and expanded to accommodate additional features of the region and to recognise those likely to have differing substrates and influence on oceanography. This approach was used to improve the technique as a predictor of physical conditions that may influence benthic communities. Key features of the Antarctic continental shelf are shelf banks, shelf deeps and cross shelf valleys, as defined in Table 1. The continental slope is generally comprised of a narrow upper slope and a broader lower slope, which abuts the abyssal plain. Much of the Southern Ocean away from continental margins is defined as rough seafloor, due to the protrusion of small basement hills and ridges beneath the sediment surface. This seafloor is broken in places by troughs, trenches, mid ocean ridges, seamounts, and elongated seamount ridges. Large plateaus are also prominent features.

Table 1 Description of geomorphic features mapped in this study.

Feature	Description
Shelf bank	Banks on the shelf at depths <500 m and therefore subject to iceberg scouring.
Shelf deep	Areas on the shelf delineated by closed contours deeper than 500 m.
Cross shelf valley	Shelf depressions, commonly shallower than 500 m, that are connected to the shelf edge by valleys.
Coastal terrane	Inshore areas at depths delimited roughly by the 200 m contour, and therefore within the photic zone.
Island coastal terrane	Mapped as for coastal terrane around large, rugged islands.
Iceshelf cavity	Areas beneath floating ice tongues.
Upper slope	Upper limit of the continental slope mapped as position at which the rate of change in gradient is at a maximum, to a lower limit ~2500 m where the gradient reduces.
Lower slope	Mapped from ~2500 m, or where there is a reduction in slope gradient, to a lower limit at the point where canyons are no longer obvious (~3500 m).
Trough mouth fan	Broad aprons of sediment on the upper slope, extending from the shelf break to 2500–3000 m water depth.
Structural slope	Low relief topographic features formed from underlying structures, such as basement protrusions, that extend beyond the lower slope.
Margin ridges	Large protrusions extending hundreds of meters above the abyssal plain formed from igneous or basement intrusions.
Marginal plateau	Areas of relatively flat seafloor that extend from the continental margin, but are separated from the shelf by a saddle.
Abyssal plain	Smooth, sediment covered area of seafloor.
Contourite drift	Mounds of sediment that rise gently above the surrounding sea floor, constructed by strong bottom currents.
Rough seafloor	Rugged seafloor consisting of a mixture of hard and soft substrates reflecting the protrusion of small basement hills and ridges beneath the sediment surface.
Seamount	Roughly circular areas which rise above the surrounding sea floor by at least 1000 m.
Seamount ridges	Elongate ridges which are hundreds to thousands of meters high relative to the surrounding seafloor.
Mid ocean ridge valley	Elongate troughs several hundreds of meters deeper than the rift shoulders, with a pronounced central rift valley.
Fracture zone	Steep cliffs developed on major crustal fracture zones, formed during rifting and seafloor spreading.
Trough	Closed elongate depressions more than 4500 m deep and hundreds of kilometres long. Mostly straight.
Trench	Arcuate areas of very deep ocean floor, more than 5000 m deep. Formed by subduction of oceanic crust at convergent plate margins.
Island arc	Arcuate ridges capped with volcanic islands formed adjacent to subduction zones.
Volcano	Active volcanoes that impinge directly on the marine environment.
Plateau	Relatively flat regions elevated by at least a few hundred meters above the surrounding seafloor. The edge is defined as the line of maximum change in slope above the region that slopes to the ocean floor.
Plateau slope	Broad sloping regions around the margins of larger plateaus.
Ridge	Elongate ridges that extend from large plateaus and other features.
Wave-affected bank	Areas of banks shallower than 200 m which are likely impacted by large, long period swells and storm waves.
No data	Features could not be mapped due to lack of data. Usually in areas of heavy sea ice accumulation.

4. Sediments

Sedimentation on continental margins is comprised of terrigenous and biogenic sources. On the Antarctic margin, terrigenous sediments are deposited predominantly by glacial processes that were active during previous glaciations and are still active today. During periods of glacial advance to the shelf edge, large trough mouth fans, such as the one located off the Prydz Bay continental shelf (Map 2), have been built from subglacial debris melted from the base of the ice sheet (O'Brien *et al.* 2007). Terrigenous sediments are also contributed to the seafloor via aeolian processes and ice rafting (McCoy 1991). Biogenic sediments are composed of the calcareous and siliceous remains of organisms living at the seafloor and in the water column. Deposition and preservation of biogenic remains, however, is complicated by dissolution and current transport (for further discussion see Smetacek 1985, Nelson *et al.* 1995, Hauck *et al.* 2012).

Sediment type is strongly linked to morphology on the Antarctic margin (Fig. 1, Post 2013). Depocenters for fine grained biosiliceous material occur in deep shelf troughs and channels, as well as at abyssal depths (McCoy 1991, Post 2013). A broad band of biosiliceous sediments occurs around the Antarctic margin between 50° and 70°S due to high productivity in the surface waters associated with the Antarctic Zone (see discussion in the Physical Oceanography section). Extensions of biosiliceous sediments north of this band, as occur immediately east and west of the Mid-Atlantic Ridge (and in other regions, see McCoy 1991), reflect redeposition by bottom currents (McCoy 1991). Coarser sands and gravels occur in small pockets, associated with shelf banks, reflecting the exposure to stronger currents and frequent iceberg scouring in these environments (Post 2013). The continental slope also contains coarser sediments (Fig. 1) due to reworking by down-slope processes in the rugged slope canyons. Carbonate content tends to be higher on the upper slope/shelf break, with peaks in carbonate content around the Antarctic margin found at depths of 150–200 m and 600–900 m (Hauck *et al.* 2012). On the East Antarctic margin, peaks in carbonate concentration on the upper slope are associated with known occurrences of carbonate-building hydrocoral communities (Post *et al.* 2010), although winnowing of clay and silt by strong shelf edge currents likely enhances the concentration of carbonate in upper slope sediments (Hauck *et al.* 2012). Fine-grained carbonate sediments are also extensive on ridges, plateaus and rises, where these features are

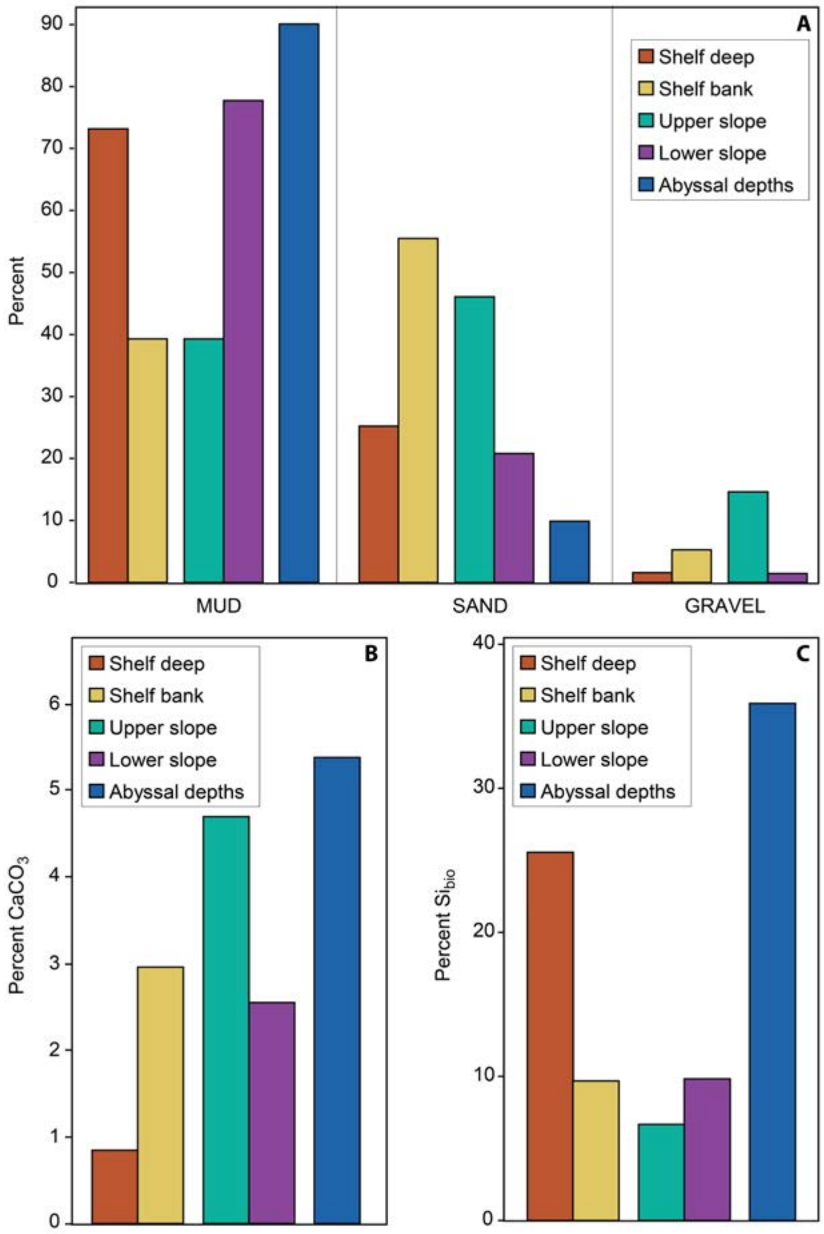


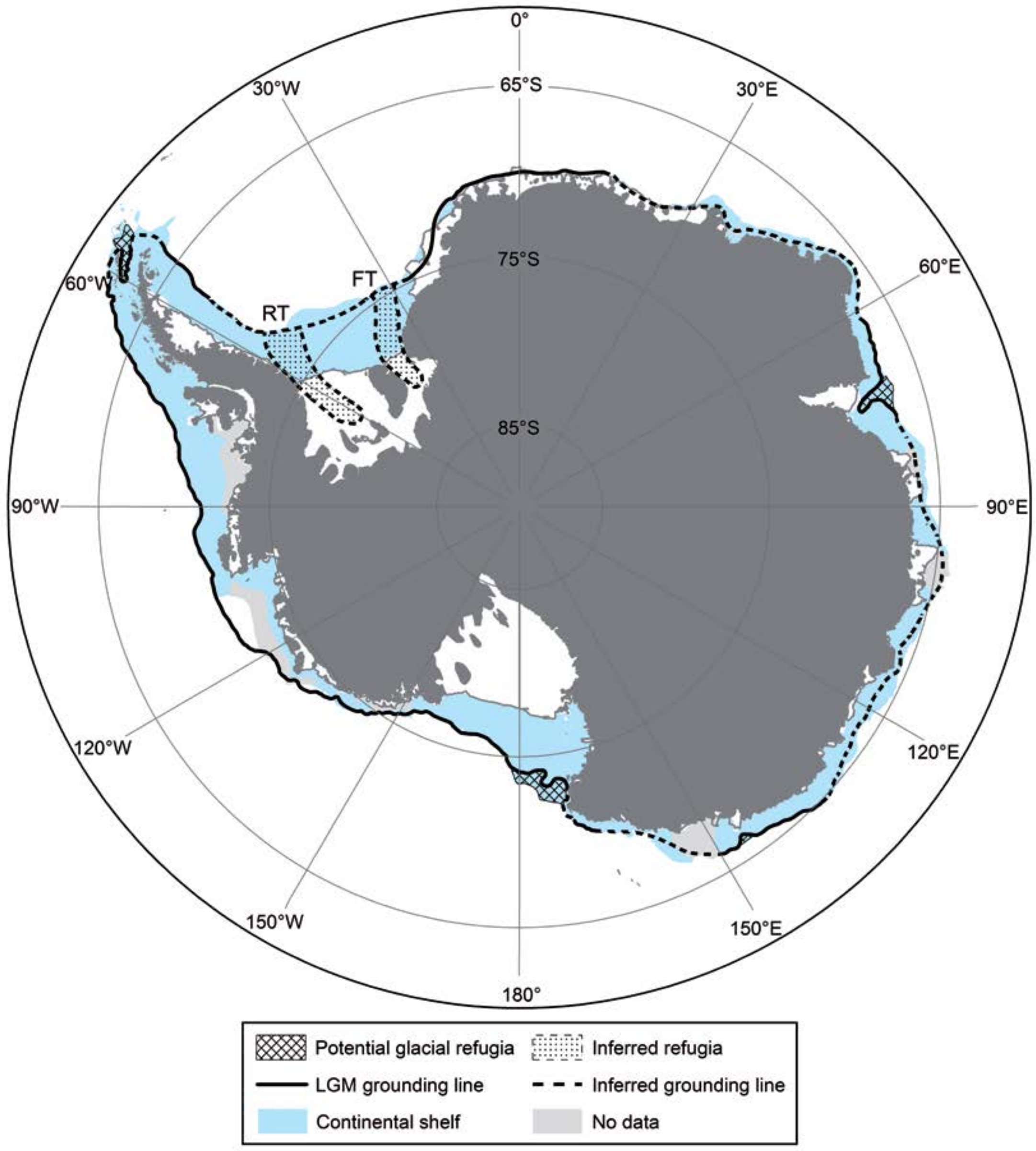
Figure 1 (a) Sediment grainsize; (b) percent calcium carbonate; (c) percent biogenic silica in relation to geomorphic features for the East Antarctic margin, south of 60ºS (from Post 2013). Note that no gravel has been sampled from abyssal depths.

above the level of the carbonate compensation depth (McCoy 1991). Sediment data is sparse on many parts of the Antarctic margin, but the close linkages between sediment type and morphology mean that these features can be used to expand our understanding of the nature of the seabed environment.

Numerous studies have demonstrated the significance of substrate properties to the distribution of benthic biota. The distinction between hard and soft substrates has been associated with distinct species assemblages (Williams & Bax 2001, Beaman & Harris 2007), while the grainsize composition of the sediments, and particularly the mud content, has been shown to have a strong correlation to the benthic communities in a range of settings. These regions include the Antarctic margin (Beaman & Harris 2005, Koubbi *et al.* 2010, Post *et al.* 2011), the NW Atlantic (Thouzeau *et al.* 1991, Kostylev *et al.* 2001), the Great Barrier Reef (Beaman & Harris 2007, Pitcher *et al.* 2007) and the Gulf of Carpentaria, NE Australia (Long *et al.* 1995, Post *et al.* 2006).

5. Last glacial maximum grounding line

The Antarctic shelf fauna has been strongly influenced by the expansion and retreat of the Antarctic ice sheets on glacial–interglacial time scales (Clarke *et al.* 1992, Thatje *et al.* 2005). The expansion of the ice sheets across the continental shelf during glacial periods largely eradicated the available shelf habitats and evidence suggests that these shelf fauna may have migrated to either the Antarctic slope or the deep sea (e.g. Zinmeister & Feldmann 1984, Brandt 1991, Brey *et al.* 1996). In some regions, however, shelf fauna may have found refugia during glacial periods beneath floating ice shelves or small ice-free areas in regions where grounded ice did not advance to the edge of the continental shelf. Geological evidence suggests that during the last glaciation the ice sheets did not completely ground to the shelf edge in the western Ross Sea (Licht *et al.* 1996, Shipp *et al.* 2002), Prydz Bay (Domack *et al.* 1998, O'Brien *et al.* 1999), a small part of George V Land (Beaman & Harris 2003), the northern tip of the Antarctic Peninsula (Davies *et al.* 2012) and possibly in at least parts of the Filchner and Ronne Troughs in the Weddell Sea (Davies *et al.* 2012, Hillenbrand *et al.* 2012, Larter *et al.* 2012), though further multibeam and sediment data are required to clarify the extent of the grounding line in this region. These areas where the ice sheet did not ground to the shelf edge contain potential shelf refugia as shown on Map 3.



Environmental Setting Map 3 The last glacial maximum (LGM) grounding line (as compiled by Livingstone *et al.* 2012) together with the location of the shelf edge (from O'Brien *et al.* 2009) has been used to determine areas of potential shelf refugia. RT is the Ronne Trough and FT is the Filcher Trough. The extent of the LGM grounding line in these two regions remains uncertain (Davies *et al.* 2012).

6. Sea ice

6.1. Physical characteristics of sea ice

Sea ice is a major feature of the Antarctic marine realm and has profound and diverse effects on its ecosystems. The extent of sea ice ranges from approximately 3 million km^2 in February to 18 million km^2 in September (Cavalieri & Parkinson 2008), making it one of the largest seasonal physical changes in surface conditions anywhere on the planet. Map 4 shows the annual cycle of sea ice extent around the Antarctic coast. The seasonal cycle in sea ice extent is characterised by slow and steady growth from March to September, followed by relatively rapid decay, particularly in December and January. Minimum extent in most regions is typically achieved in February or early March, with maximum extent occurring in September (Gloersen *et al.* 1992).

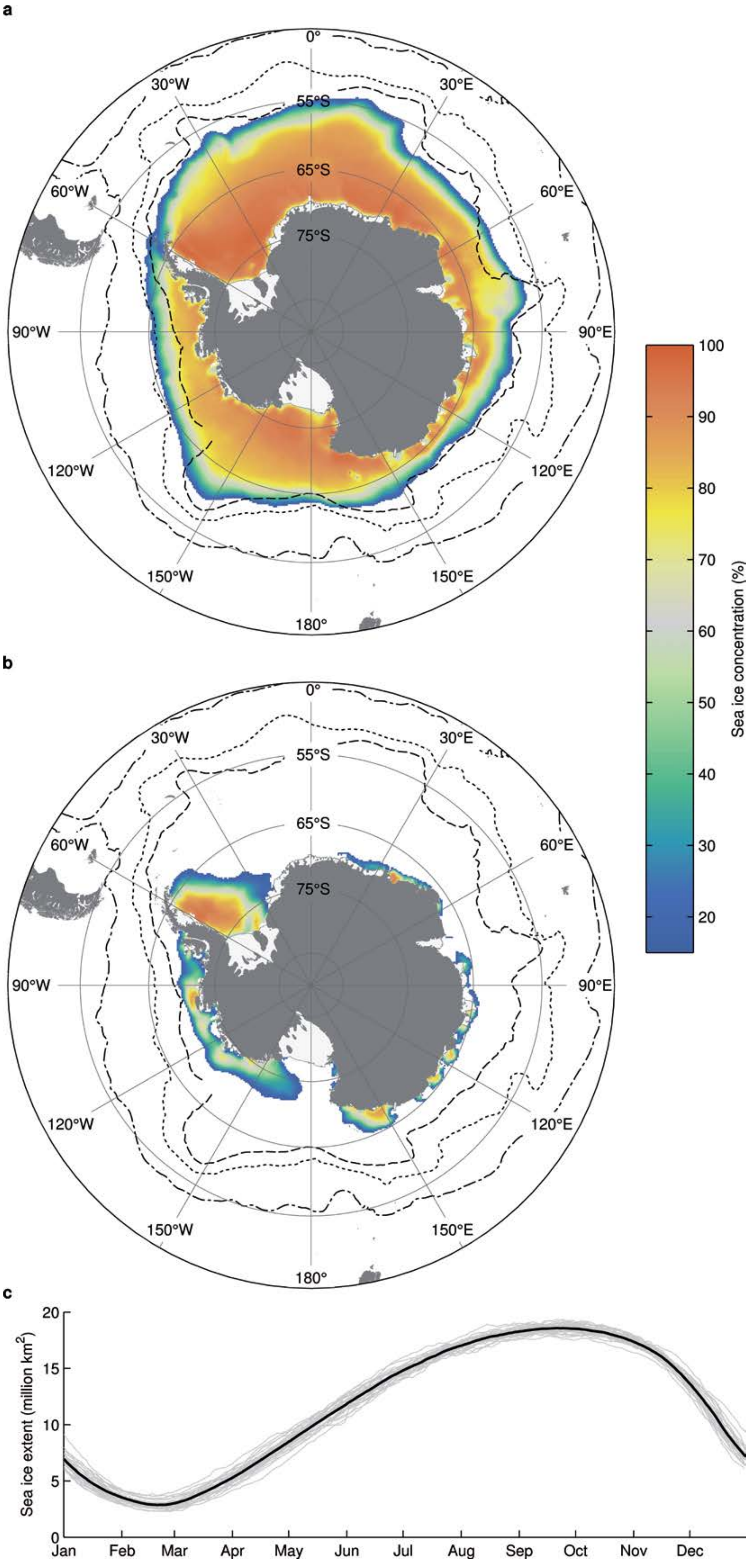
Sea ice can be broadly classified into pack and fast ice. Pack ice is moved across the ocean by wind and currents and is predominantly annual, with a typical mean thickness of less than 1 m (Worby *et al.* 2008) and a maximum thickness of 2 m, although dynamically-thickened ice can exceed this considerably. In some regions, particularly the Weddell Sea, pack ice can be perennial, reaching a thickness of 3–4 m and with ridged and rafted surfaces. Landfast ice, or fast ice, is mechanically locked onto coastal features, fixed to grounded icebergs, or grounded upon shoals (World Meteorological Organisation 1970). Since fast ice is often contiguous with the coast, it has implications for biota whose habitat includes the near-coastal zone. In East Antarctica, fast ice typically forms "upstream" (on the eastern side) of protrusions into the westward-flowing Antarctic coastal current (e.g. grounded icebergs and coastal promontories), with a coastal polynya often located on the corresponding "downstream" (western) side (Fraser *et al.* 2012).

Polynyas (see Map 5) are regions of low sea ice concentration enclosed within higher-concentration sea ice (Barber & Massom 2007). Coastal polynyas typically form in regions where strong, persistent, offshore winds (e.g. katabatic winds) exist. The wind advects pack ice away from the coast, exposing open water. Polynyas are particularly prevalent in the East Antarctic sector, where pack ice is dynamically steered to the north by coastal protrusions into the Antarctic coastal current. Transient offshore polynyas can also exist within the pack ice zone (e.g., the recurring Cosmonaut Polynya, at ~40°E). These are caused either by divergent atmospheric/oceanic flow or an input of heat from the ocean (Barber & Massom 2007). Polynyas are important areas of elevated primary production (Arrigo & van Dijken 2003) and also provide access to the water for higher predators such as penguins and seals. Similarly, flaw leads (narrow strips of open water) typically form when divergent ice conditions occur at the shear zone between pack ice and fast ice or the coast.

The general characteristics of Antarctic sea ice regimes vary by sector, and are influenced by factors such as latitude, ocean currents, and coastal topography. The Ross and Weddell Sea sectors are dominated by their large embayments and ocean gyre circulations. The Weddell Sea has the largest latitudinal extent of sea ice, whereas the East Antarctic sector (~30°–160°E) has a relatively narrow sea ice zone. Sea ice dynamics in the coastal zone can be complex, with influences from coastal currents, icebergs (grounded and drifting), ice shelves, glacier tongues, fast ice, and coastal polynyas. In sectors with narrow sea ice zones (e.g. 90°–150°E), blocking features such as glacier tongues can have an appreciable effect on the overall regional sea ice dynamics (Massom *et al.* 2013).

6.2. Sea ice and climate change

In contrast to the recent rapid decline in sea ice extent observed in the Arctic (Stroeve *et al.* 2008), a slight but significant positive trend of approximately +1.2% per decade is observed in overall Antarctic sea ice extent over the period 1979–2008 (Cavalieri & Parkinson 2008, Comiso 2010). However, differing trends in sea ice extent are observed on a regional basis, depending largely on the strength and phase of various modes of atmospheric variability (see Comiso 2010 for references). The only two statistically significant regional trends are a decrease in the Bellingshausen/Amundsen Seas sector (60°–130°W) of -7.1% per decade, and an increase in the adjacent Ross Sea sector (130°W–160°E) of +4.9% per decade, likely driven by atmospheric forcing (see Massom *et al.* 2006, Comiso 2010 for more details). The remaining sectors (Weddell Sea, 20°E–60°W; Indian Ocean, 20°–90°E; and Western Pacific Ocean, 90°–160°E) all show slight but non-significant positive trends (Comiso 2010). However, the Indian and Western Pacific Ocean sectors show considerable variability in trends at



Environmental Setting Map 4 Mean (a) September; (b) February Antarctic sea ice concentration, averaged over 1979–2010 from monthly SMMR-SSM/I passive microwave estimates (Cavalieri *et al.* 1996, updated 2010). The dashed line shows the southern Antarctic Circumpolar Current front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009). The annual cycle of sea ice extent is shown in (c), with individual years (1979–2010) shown as grey lines and the mean in black.

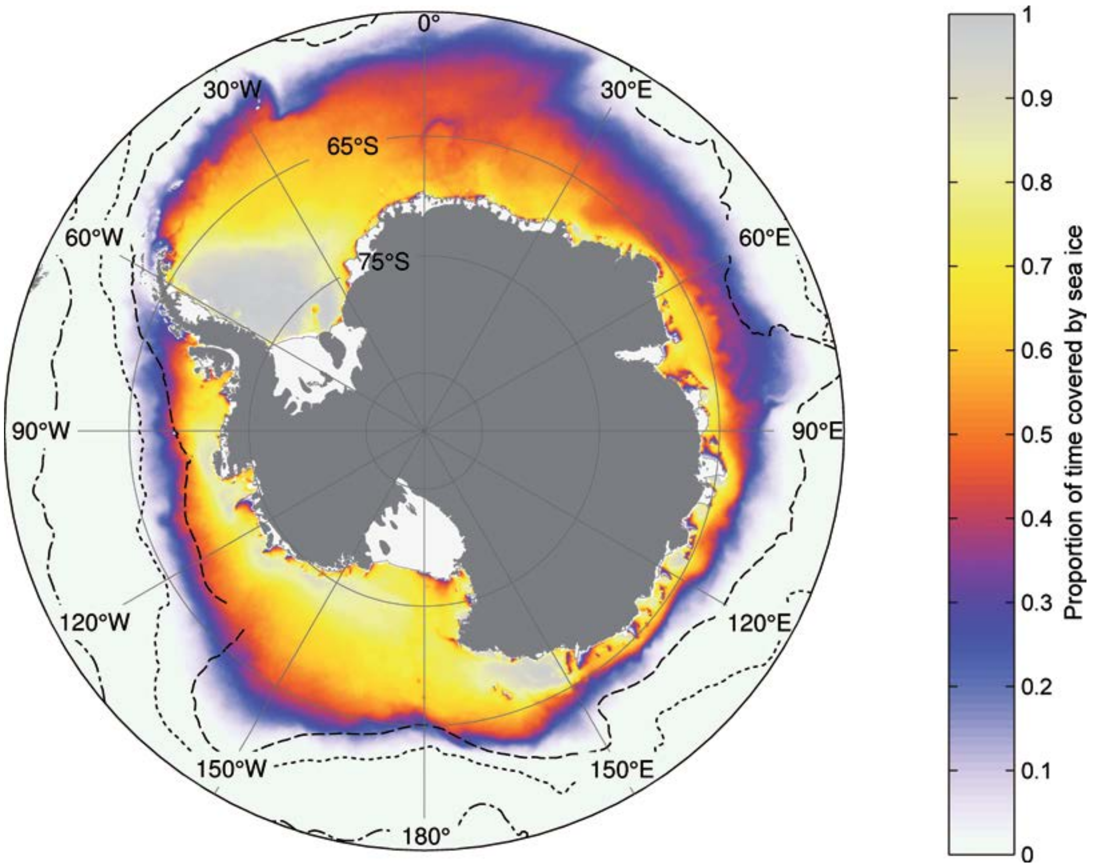
sub-regional spatial scales (Massom *et al.* 2013).

Sea ice responds rapidly to oceanic (e.g. ocean heat flux, waves, swell, ocean currents), atmospheric (air temperature, winds) and radiative (shortwave/longwave flux) forcing, but also influences all three components via complex feedback mechanisms (see Thomas & Dieckmann 2010, and references therein). The future state of Antarctic sea ice therefore depends strongly on the future climate state. Climate models generally project increases in Antarctic surface air temperature, snowfall, storminess and waviness, leading to a general decrease in pack ice cover (Bentley *et al.* 2007, Bracegirdle *et al.* 2008, Turner *et al.* 2009).

6.3. Sea ice organisms

Sea ice provides a habitat for various groups of organisms including bacteria, algae, fungi, heterotrophic protists, and invertebrates. The organisms inhabit a network of interconnected brine pockets that form the so-called brine channel system. Brine-filled pockets form during freezing of seawater as salt-ions are not incorporated into the crystal lattice of sea ice. The brine volume fraction (i.e. the fluid fraction of sea ice) is a function of sea ice bulk-salinity and temperature and ranges from ~1% in cold ice to ~20% in warm ice (ice that is near the freezing temperature of seawater). A brine volume fraction of 5%, characteristic for sea ice with a temperature of -5°C and a bulk-salinity of 5, is considered to be the theoretical threshold for brine percolation and fluid transport (Golden *et al.* 1998, Golden *et al.* 2007). Brine volumes below 5%, along with thermohaline stratification of the brine channel system, can limit brine convection and thus nutrient availability in sea ice interior layers (Tison *et al.* 2008, Vancoppenolle *et al.* 2010). Brine salinity is a function of ice temperature and is therefore characterised by strong vertical and seasonal variability. For example, at a temperature of -10°C (a typical winter sea ice surface temperature) sea ice brine salinity equals approximately 141, i.e. more than 4 times the salinity of open ocean seawater (Petrich & Eicken 2010). Thus, surface and interior parts of sea ice can provide an extremely harsh environment, both in terms of temperature and osmotic pressure. However, sea ice organisms are generally well adapted to these conditions and form distinct biological communities in these layers (Meiners *et al.* 2009, Arrigo *et al.* 2010, Meiners *et al.* 2011).

In terms of biomass, sea ice communities are generally dominated by algae, and in particular by diatoms. Algae become incorporated into sea ice during ice formation by various physical mechanisms, including nucleation, scavenging of cells by rising frazil crystals and wave-field pumping (summary in Spindler 1994). Some of the algal cells survive incorporation and continue to grow in their new semi-confined environment. Ice algal standing stocks can be extremely high and can exceed biomass values of phytoplankton inhabiting under-ice water by 1–3 orders of magnitude (Arrigo *et al.* 2010). Ice algal vertical distribution is distinctly different in fast ice versus pack ice (Fig. 2). Fast ice is commonly dominated by bottom communities that develop at the sea ice – water interface as a result of favourable growth conditions in terms of light, temperature, brine salinity and nutrient availability. Vertical algal distribution in pack ice comprising bottom, interior and surface communities varies across different regions around Antarctica and is influenced by sea ice growth, deformation processes, snow loading and surface melt processes (e.g. Fritsen *et al.* 1994, Ackley *et al.* 2008, Meiners *et al.* 2012). Sea ice algae have been estimated to contribute up to 25% of the overall primary production of the Antarctic sea ice zone (Arrigo & Thomas 2004). Ice algal communities are adapted to low light levels, can grow early in the season and are believed to extend the period of primary production in large parts of the Southern Ocean. Thus sea ice communities provide an important early-season food source for pelagic herbivores during late winter and early spring, when food in the water-column is scarce.



Environmental Setting Map 5 Map showing the proportion of time the ocean is covered by sea ice of concentration 85% or more, derived from AMSR-E satellite-derived estimates of daily sea ice concentration at 6.25 km spatial resolution (Spreen *et al.* 2008). Coastal polynyas are visible as areas of blue near the coast, and are particularly prevalent in the East Antarctic sector. The dashed line shows the southern Antarctic Circumpolar Current front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).

The most commonly encountered sea ice invertebrates are crustaceans, principally copepods, which live either within the brine channel system of the ice-crystal matrix or at the under-ice surface (Arndt & Swadling 2006). Amphipods, including *Eusirus antarcticus* and *E. tridendatus* (Krapp *et al.* 2008), and Antarctic krill *Euphausia superba* are also found living under the sea ice, particularly around creviced and rough surfaces where they can be protected from predators while foraging on the abundant ice algae that can be present (Arndt & Swadling 2006). Other groups that have been observed include foraminiferans, turbellarians, nematodes, gastropods, and ctenophores (Kramer *et al.* 2011). The ephemeral nature of sea ice means that most species associate with ice for only a part of their life cycle, though the extent of the association varies between species and geographic locations (Arndt & Swadling 2006).

6.4. Influence of sea ice on pelagic organisms

In the sea ice zone, pelagic primary production and biomass (i.e. in the water, rather than the sea ice itself) are affected by the ice in multiple and complex ways. Ice, especially when snow-covered, attenuates light by 1–2 orders of magnitude, thus imposing a strong limitation on phytoplankton growth in the under-ice pelagic realm (Eicken 1992, Fritsen *et al.* 2011). Conversely, sea ice serves as a temporal reservoir for nutrients, for example by accumulating the micro-nutrient iron during sea ice formation and releasing it into iron-depleted surface waters during ice melt in spring and early summer (Lannuzel *et al.* 2007, Lannuzel *et al.* 2010, Wright *et al.* 2010). In addition, ice-associated microalgae released from pack ice are thought to serve as inocula for spring phytoplankton blooms (Lizotte 2001, Raymond *et al.* 2009). The release of nutrients and algae in combination with meltwater-induced stratification of surface waters can trigger ice-edge blooms, which can result in strong increases in regional Southern Ocean primary and export productions (Smith & Nelson 1985, Buesseler *et al.* 2003, Arrigo & Thomas 2004, Smith & Comiso 2008, Shadwick *et al.* 2013). However, the formation of ice-edge blooms is moderated by other processes including current-generated fronts, polynya expansion, sea ice advection and wind stress patterns (Fitch & Moore 2007, Smith & Comiso 2008, Schwarz *et al.* 2010). As a result, the productivity in the marginal ice zone is often similar to open water productivity and the contribution of ice-edge bloom production to overall Southern Ocean production is considered to be low (Arrigo *et al.* 2008). Ice-edge blooms are most productive on the continental shelves, and generally no sustained blooms occur in waters exceeding 1000 m in depth (Smith & Comiso 2008).

In addition to its effects on overall phytoplankton productivity, sea ice also strongly influences pelagic community composition. Relationships have been identified between the biogeographic distribution of several species of modern, sediment-based, Southern Ocean diatoms and satellite-based sea ice duration, concentration and extent (Armand *et al.* 2005). This study highlights the role of sea ice in structuring diatom community composition and geographic distribution of key Antarctic phytoplankton species. The Southern Ocean diatom sediment record promises a useful tool to understand impacts of changing sea ice on Southern Ocean ecosystem structure prior to the introduction of satellite and historical ship records, and, combined with field and physiological studies, may also help to predict the responses of Southern Ocean phytoplankton communities to future sea ice conditions.

Southern Ocean zooplankton and nekton distributions are also influenced by sea ice conditions (Nicol *et al.* 2000, Ojima *et al.* 2013). The life cycle of krill with respect to sea ice has been a particular focus of study. In the southwest Atlantic sector, for example, it has been shown that there is a correlation between the extent of winter sea ice and the subsequent recruitment of krill (e.g. Atkinson *et al.* 2004). It has been hypothesised that krill, particularly larvae, are dependent on the microbial and diatom communities that grow on the underside of ice for food (Stretch *et al.* 1988, Smetacek *et al.* 1990, Frazer *et al.* 1997). Adult female krill that feed well under ice in winter enter the spring in a well-nourished condition and spawn successfully (Quetin & Ross 2003). Similarly, juvenile krill that are able to feed under ice during their first winter have an increased chance of survival. Unlike adults, juvenile krill are not able to tolerate periods of starvation (O'Brien *et al.* 2011), and so multiple winters of reduced sea ice may eventually lead to a reduction in krill biomass.

Where ice-edge blooms occur, they provide an important spring and summer food-source for pelagic herbivores including krill (Nicol *et al.* 2000). Other taxa that take advantage of the high ice algal biomass in spring include amphipods, copepods and pteropods (Swadling, unpublished). Some amphipods, such as *Gondogeneia antarctica* (cited as *Pontogeneia antarctica*) graze directly on ice algae, while others feed on detritus-algae aggregates that develop near the ice underside (Richardson & Whitaker 1979). Small copepods, such as *Paralabidocera antarctica* and *Stephos longipes*, graze heavily on ice algae (Swadling *et al.* 2000) and form part of the trophic pathway from ice algae to the ice fish *Pagothenia borchgrevinki* in fast ice habitats (Hoshiai *et al.* 1989). There appear to be no large copepods that rely on sea ice as their only food source, although ice algae can form part of the diet during certain seasons. The biomass dominant *Calanus propinquus*, for example, is believed to overwinter part of its population in surface waters where it takes advantage of ice algae as a food source. For higher predators such as penguins, seals, and flying seabirds, sea ice provides habitat and foraging grounds, and is important for reproduction, and for moulting for birds and seals (Ainley *et al.* 2003). However, the effects of sea ice variability on biota are again complex. Emperor penguins *Aptenodytes forsteri* rely on stable fast ice conditions for breeding and rearing chicks, but extensive fast ice (which the birds must cross in order to access open water for foraging) can impact breeding success (Massom *et al.* 2009). Adélie penguins *Pygoscelis adeliae* nest on ice-free land, but can be similarly affected by coastal fast ice (Emmerson & Southwell 2008). Polynyas are therefore an important factor driving the colony locations of these species. The sea ice edge, particularly during spring and summer with its associated ice-edge phytoplankton blooms, is a productive foraging ground for higher predators such as humpback whales (Thiele *et al.* 2004, Gales *et al.* 2009) and fur seals (Boyd *et al.* 2002). From the ice edge, diving predators can access under-ice communities of fish and invertebrate prey, which are typically more abundant than in open waters (Brierley *et al.* 2002, Flores *et al.* 2012). Variations in sea ice conditions can thus have a direct effect on the foraging success of predators — even sub-Antarctic-breeding predators, which can be excluded from productive Antarctic foraging grounds by extensive sea ice (Thums *et al.* 2011).

6.5. Influence of sea ice on benthic organisms

Sea ice also affects benthic biota. At a local scale, such impacts can be very significant because most benthic organisms cannot escape, reinvade or drift back into their usual habitat, unlike the nekton and plankton. The direct impacts (e.g. ice scour) are most extreme in shallow water, and so coastal habitats tend to have low species diversity and often low abundance, and are dominated by those few animals and algae that are able to withstand the harsh conditions. Limpets tend to be one of the best survivors, with high abundances despite the threat of ice scour (Gutt 2001). In McMurdo Sound, ice scouring is associated with macroalgal depth zonation: the algae *Iridea cordata* occurs from 3–10 m, *Phyllophora antarctica* dominates from 6–18 m and the encrusting coralline algae *Phymatolithon foecundum* dominates from ~18–60 m (Miller & Pearse 1991). The frequency of ice disturbance decreases with depth, with an associated increase in diversity (e.g. Barnes 1995).

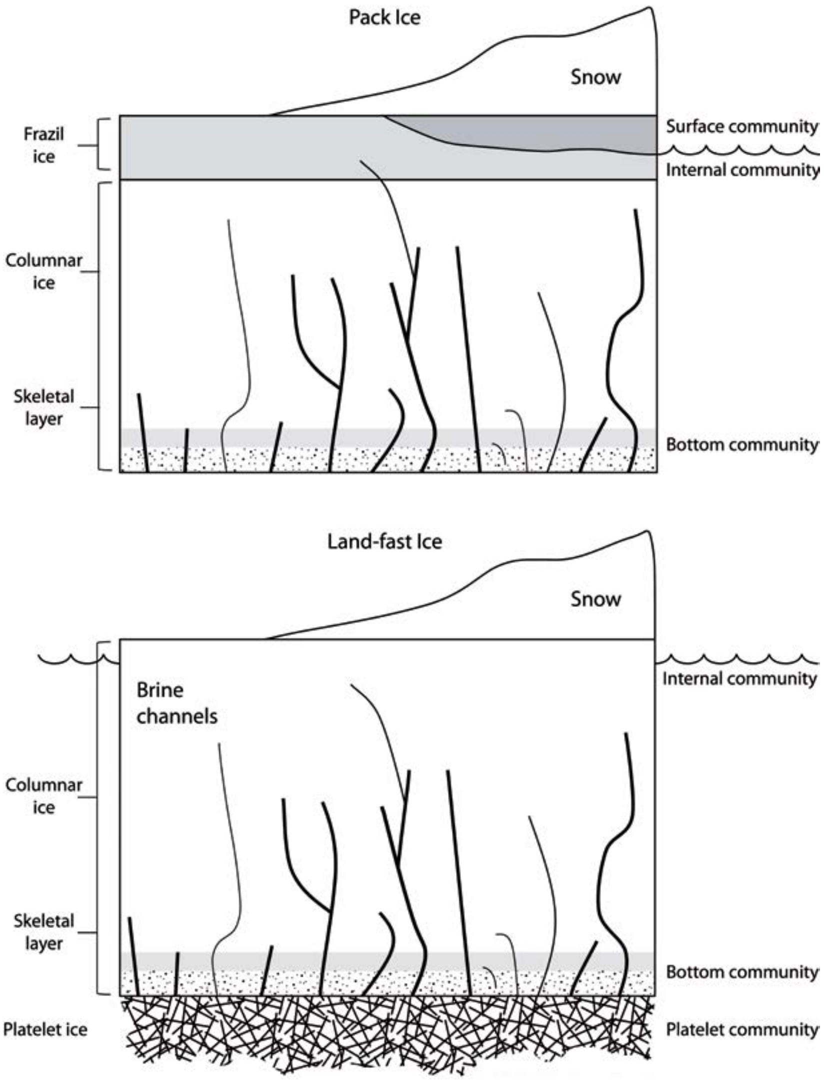


Figure 2 Schematic illustration of pack ice and land-fast ice showing the major physical features and locations of microbial habitats (redrawn from Arrigo & Thomas 2004).

Anchor ice (submerged ice that is attached to the sea floor) also directly impacts on benthic fauna, with a 2 m^2 piece of ice able to lift 25 kg of sediment, including any epifauna living within its radius (Dayton *et al.* 1970). In McMurdo Sound during the 1960s and the early 1980s, high levels of anchor ice disturbance occurred to depths of 30 m, and at this time the sponge *Homaxinella* and its predators were rare along the shoreline (Dayton 1989). During the early 1970s changes in oceanographic conditions resulted in very low levels of anchor ice disturbance, and there was massive recruitment of *Homaxinella*, which subsequently covered up to 80% of the seafloor.

Sea ice and its snow cover also influence the structure of benthic ecosystems by regulating the light levels that reach the sea floor. In the Davis region of Prydz Bay, areas of hard substrate which are ice-free for significant periods of the year are covered with abundant algal growth (*Himantothallus* and *Iridea*), and have relatively low abundances of attached invertebrates (O'Brien *et al.* 2012). Rocky areas with more persistent sea ice cover, by contrast, are dominated by attached invertebrates. Similar responses to sea ice cover have been observed on the Windmill Islands coast, near Casey (Johnston *et al.* 2007), and at Signy Island in the South Orkneys (Barnes 1995). At high latitudes, the summer season is short and overall light budget is low (Map 6a), and so even relatively minor variations in the timing of sea ice formation and retreat can make considerable differences to the total seasonal light reaching the water column (Clark *et al.* 2013). The seasonal benthic light budget at a given location can be approximated by using the incident clear-sky radiation (i.e. ignoring the effects of clouds) over the season, modulated by the sea ice cover. When the location is covered by sea ice, it is assumed that negligible light penetrates the snow/ice cover. The resultant seasonal light budget (Map 6) shows considerable heterogeneity around the Antarctic coast, largely but not exclusively mirroring the variability in sea ice cover (Map 5).

7. Southern Ocean Physical Oceanography

7.1. Antarctic Circumpolar Current circulation

The Antarctic and its marine ecosystems are heavily influenced by the circulation of the surrounding Southern Ocean. Because the Southern Ocean is zonally continuous around the globe, the Antarctic and its coastal seas are insulated to some extent from the warmer lower latitudes. This permits the existence of the huge extent of winter sea ice discussed in the previous section as well as the presence of large ice shelves and grounded ice below sea level. The Antarctic Circumpolar Current (ACC) flows from west to east around the Southern Ocean (Map 7) and is the most powerful current on Earth (134–164 Sv, where 1 Sv is a flow of 10^6 m^{3}s^{-1}). The ACC exerts a massive influence on the global climate (Cunningham *et al.* 2003, Griesel *et al.* 2012). The eastward flowing ACC and the overlying west wind drift separates the warmer sub-tropical anticyclonic gyres (circular wind driven ocean currents) that exist in the Pacific, Atlantic and Indian Ocean basins from the cold sub-polar regime, consisting of the Weddell and Ross Sea cyclonic gyres and the Antarctic coastal and shelf waters. At the broadest scale the ACC is driven by a combination of wind stress from the strong mid-latitude westerly winds as well as the persistent density gradient between north and south driven by buoyancy loss in the sub-polar regions. By connecting the major ocean basins the ACC allows an exchange of water properties between them, and is the central link in the global thermohaline circulation, or 'global conveyor belt' that moves heat, freshwater, CO_2, nutrients, and other tracers around the globe.

The ACC itself is made up of numerous narrow, deep reaching boundaries in water mass properties called fronts. The two most distinct and continuous circumpolar fronts are the Sub-Antarctic Front (SAF) and the Polar Front (PF), but in some sectors up to nine distinct fronts have been identified, which tend to be very dynamic, meandering, merging and splitting again over time (Sokolov & Rintoul 2009). The pathways of the fronts are strongly determined by topographic constraints, and large diversions in the flow occur around features such as Drake Passage and the East Scotia Ridge, Crozet, Kerguelen and Campbell Plateaus, and to a lesser extent the mid-ocean ridges in the Pacific and Indian Oceans. These topographic features often 'pin' fronts in place, but over flatter regions, particularly downstream of topographic diversions, fronts tend to be more dynamic, meandering and spinning off small scale eddies.

The large temperature and salinity contrasts between the north and south sides of the ACC result in steeply sloping isopycnals across the current, which causes strong local maxima in current speed (50–100 cm.s^{-1}). Mixing and transport preferentially occurs along isopycnals rather than across them, so these sloped isopycnals represent an overturning pathway between the deep ocean interior and the ocean surface (Fig. 3). The overturning of water masses in the Southern Ocean acts to ventilate the ocean interior by subducting surface waters that exchange oxygen and CO_2 with the atmosphere into the deep ocean, as well as renewing the surface layers with nutrient-rich upwelled deep water. Relatively warm and saline Circumpolar Deep Water (CDW) is brought up to the surface along the sloping isopycnals by mesoscale eddies, driving mixing along isopycnals and vertical pumping on the southern flank of the ACC. The vertical pumping is driven by divergent wind-driven (Ekman) currents occurring at the boundary between the westerly winds driving the ACC and the easterlies closer to Antarctica, sometimes known as the Antarctic Divergence. Water upwelled in this fashion is either exported southwards or northwards by the Ekman transport and is modified by interaction with the atmosphere and Antarctic Surface Water (AASW). Water moving north gains buoyancy through precipitation and warming until it crosses to the north side of the ACC and is subducted below the warm sub-tropical surface water by a variety of processes to be exported from the Southern Ocean as Sub-Antarctic Mode (SAMW) and Antarctic Intermediate Water (AAIW). This upwelling of CDW and subsequent subduction of the MCDW/AAIW forms the upper cell of the meridional overturning circulation (MOC). CDW upwelled and exported to the south loses buoyancy through atmospheric cooling and some of it undergoes further transformation in specific locations around the Antarctic coastline through complex seasonal interactions with the atmosphere, ice-shelves and sea-ice. This produces very dense Antarctic Bottom Water (AABW) which sinks and spreads northwards to fill the deepest layers of the ocean. This circulation of southward CDW modification and AABW export from the Southern Ocean forms the lower limb (or deep cell) of the MOC. The Southern Ocean is therefore central to driving and renewing both the upper and lower limbs of the global MOC.

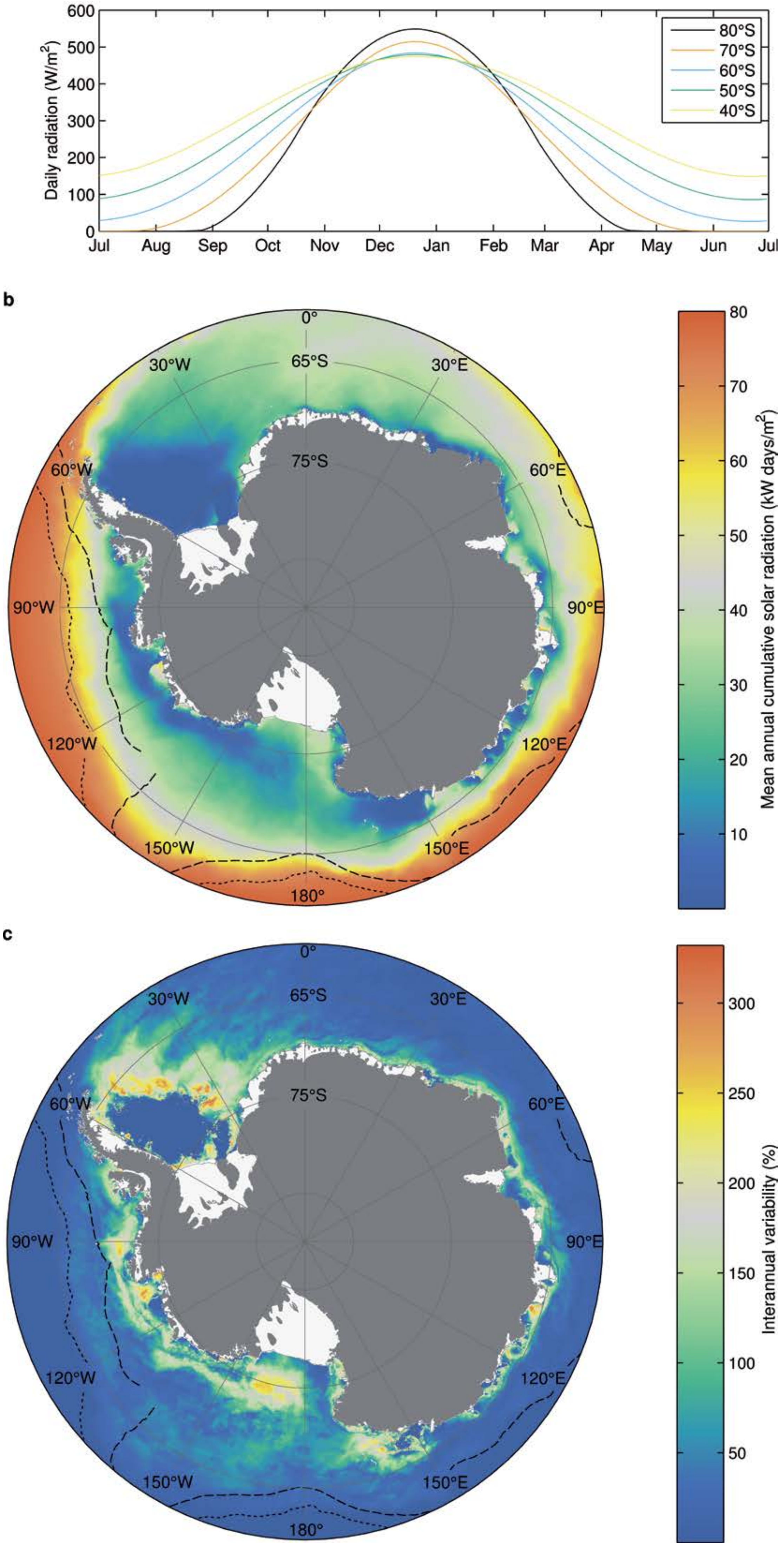
7.2. ACC fronts and zones

The ACC fronts separate regions that have distinct physical, chemical and biological properties (Whitworth 1980). The Sub-Antarctic Zone (SAZ) exists north of the SAF, and is characterised by the presence of SAMW, a thick layer of homogeneous water caused by winter time surface convection that may extend as deep as 600 m (Dong *et al.* 2008). Below this is the salinity minimum typical of AAIW that deepens northward. Below the AAIW, at depths greater than 1500 m is the CDW, the largest Antarctic water mass by volume. This may be further split into Upper CDW (UCDW) and Lower CDW (LCDW). UCDW is characterised by an oxygen minima and nutrient maxima, while LCDW has a salinity maxima and both have high levels of dissolved inorganic carbon (Verdy *et al.* 2007). AABW fills the abyssal depths below the CDW. Its Antarctic shelf origins mean that it has high oxygen, low temperature and low salinity relative to the overlying CDW.

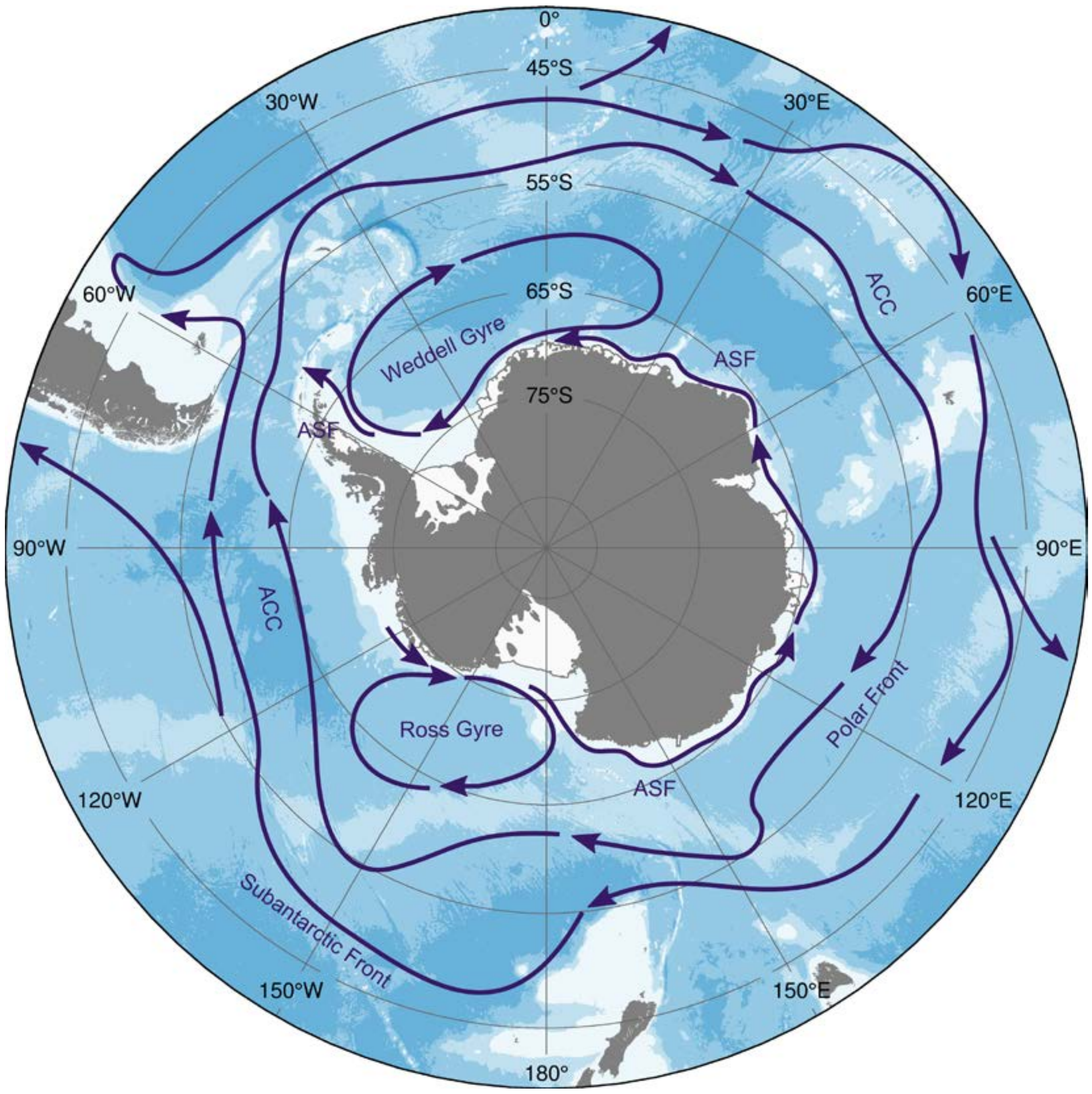
Between the SAF and the PF is the Polar Frontal Zone (PFZ). Here all water masses are found closer to the surface and the salinity minimum distinction between AAIW and SAMW is no longer apparent. The Antarctic Zone (AZ) exists south of the PF to the southern limit of UCDW, and may be characterised in summertime by the presence of a shallow subsurface temperature minimum layer at 100–300 m with temperatures <2°C (Orsi *et al.* 1995). The southern limit of UCDW, which is also commonly used to delimit the southern boundary of the ACC, has temperatures >1.8°C (e.g. Sokolov & Rintoul 2002). The T_{min} layer in the AZ is the remnants of the winter time base of the mixed layer (Whitworth & Nowlin 1987) and shoals towards the pole. The T_{min} layer is the coldest class of AASW, which is cold, fresh and with high oxygen and nutrients relative to the more northerly SAZ/PFZ surface waters. Below the T_{min} layer is the high nutrient UCDW, and its presence so close to the surface in the AZ significantly enhances the available nutrients and trace elements (Sohrin *et al.* 2000). In combination with the shallower and more stable surface mixed layer this leads to higher primary productivity and a predominance of diatoms in the AZ. This contrasts with the SAZ or PFZ where there are deep mixed layers, low silicate and few diatoms. Approximately half of the nitrate and phosphorus upwelled in the AZ are ultimately exported northwards and back into the deep ocean (Falkowski *et al.* 1998), while the large diatom blooms south of the PF account for around two-thirds of the ocean silicate burial, to such an extent that silicate concentration in the underlying ocean floor sediment may be used to trace the historical position of the PF (Tréguer *et al.* 1995). The enhanced phytoplankton productivity of this zone also results in enhanced krill and baleen whale populations (de la Mare 1997), while sperm whales and cephalopods are also found in their highest densities along the southern boundary of the ACC (Tynan 1998).

While the AZ is moderately productive, the ACC is still largely a high nutrient, low chlorophyll zone, with iron availability being a critical limiting factor to phytoplankton growth (Martin *et al.* 1990, Sohrin *et al.* 2000). One source of iron is the interaction between shallow topography and the ACC frontal jets (Moore & Abbott 2002). Bathymetry plays a direct role in driving vertically coherent upward motion through bottom pressure torque and may lift nutrient rich UCDW into the photic zone where it stimulates blooms (Sokolov & Rintoul 2007). In addition, Fe limitation can be partly reduced by direct mixing when waters pass over shallow plateaus around, for example Kerguelen-Heard and Crozet islands. This sustains the highest productivity areas found in the ACC (Chever *et al.* 2010), and can also fertilise by lateral advection surface waters that are thousands of kilometers downstream of the Fe source (Sokolov & Rintoul 2007, Mongin *et al.* 2009); see Map 8. In regions away from topographic highs, the ACC fronts are not regions of high chlorophyll productivity, even where eddy activity is great (Comiso *et al.* 1993), and usually serve to separate distinct biotic regimes, rather than being central to them (Sokolov & Rintoul 2007).

Although notoriously difficult to measure accurately, the ACC circulation appears to be largely invariant on decadal timescales, while over interseasonal and interannual periods the ACC transport typically varies by less than around 7 Sv (Meredith *et al.* 2004). This also appears to be the case for the overturning circulation, where no significant change in isopycnal slope has been observed over the last 20 years (Böning *et al.* 2008), although this is difficult to assess with confidence and may even be a sign that the upper cell of the MOC has increased in intensity (Meredith *et al.* 2012). On subannual timescales the position of the ACC fronts may be influenced by the primary modes of atmospheric variability, the Southern Annular Mode and El Niño–Southern Oscillation. These act to modify the westerly winds and may shift the ACC fronts northward or southward as well as impacting the mixed layer depth (Sallée *et al.* 2010).



Environmental Setting Map 6 The effects of latitude and sea ice cover on the light levels that enter the water column. (a) Modelled annual cycle of solar radiation for varying latitudes; (b) mean modelled annual cumulative solar radiation entering the water column, taking into account latitude and sea ice cover; (c) interannual variation in cumulative solar radiation, expressed as a percentage of the mean. The dashed line shows the Southern Antarctic Circumpolar Current Front, and the dotted line the Polar Front (mean front positions from Sokolov & Rintoul 2009).



Environmental Setting Map 7 Major Southern Ocean circulation features (adapted from Rintoul *et al.* 2001), showing the Polar and Sub-Antarctic Fronts of the Antarctic Circumpolar Current, sub-polar gyres and Antarctic Slope Front (ASF). Background colours show bathymetry.

8. Sub-polar hydrography and oceanography

8.1. Sub-polar circulation

South of the ACC there is a distinct sub-polar regime, which varies in character around the Antarctic coastline but broadly may be characterised by the presence of the easterly wind drift that drives a poleward Ekman transport, causing isopycnals to deepen towards the Antarctic continent. The region between these easterly winds and the westerly winds driving the ACC further north is sometimes referred to as the Antarctic Divergence. The divergence is so called because the westerly winds drive an Ekman transport to the north while the easterly winds drive an Ekman transport to the south; hence a divergence that produces upwelling. It is not an “ACC front” and is not usually associated with an eastward or westward current and as it is locally forced by the winds it is also not as sharply defined as the ACC fronts, instead extending over a somewhat broader range of latitudes. It may be thought of as a rough separator of the sub-polar regime from the open ocean/ACC but more because they are in the same location rather than because the Antarctic Divergence itself acts to form a boundary (Rintoul, pers. com. 2013).

The east wind drift and the sloping isopycnals it produces drive a westward flowing current around the continent, broken only at Drake Passage and on the western Antarctic Peninsula. Where the east wind drift is close to the coast or continental slope, such as between 30–150°E, the region of westward flow is narrow, while when it is further from the coast such as in the Ross and Weddell seas, the westward flow is broader and forms the southern limb of two large cyclonic circulations, the Weddell and Ross Sea gyres (Whitworth *et al.* 1998).

The Ross and Weddell Sea gyres are driven by wind stress curl and have a characteristic upward isopycnal doming in their centres (Fahrbach *et al.* 1999). Their southern limbs are typically dominated by a fast, narrow flow along the continental shelf break, while the remainder of the circulation is much broader and weaker, with geostrophic surface speeds typically less than 2 cms^{-1} (Gordon 1998). The overall circulation of the Weddell Gyre has been estimated at between 17–30 Sv (Whitworth & Nowlin 1987, Fahrbach *et al.* 1999), but may potentially be as high as 40 Sv (L. Jullion, pers. comm.). The eastern limbs of the gyres bring warm, saline CDW close enough to the continent to influence shelf slope processes, and in the eastern Weddell Sea this is sufficient to restrict autumn sea ice formation for several hundred kilometres (Heywood *et al.* 1998). The Ross and Weddell gyres have generally higher primary productivity per unit area than the ACC to the north, but are still relatively low in comparison to the continental shelves where the highest productivity in the Southern Ocean is observed (Arrigo *et al.* 2008).

The westward flowing current may be further split into the strong, narrow Antarctic Slope Current (ASC), which is topographically constrained to the upper part of the continental slope and shelf break, and the weaker westward flowing Antarctic coastal current (ACoC) that follows the Antarctic coastline over the continental shelf (Jacobs 1991). Where the continental slope is close to the coastline the two currents may merge. The ASC transport includes a strong barotropic component and varies spatially and temporally, making its exact transport difficult to estimate, but has been variously estimated at 16–45 Sv (Heywood *et al.* 1999, Bindoff *et al.* 2000, Meijers *et al.* 2010) in East Antarctica. The strength of the ASC means that it is a common path for iceberg advection around the continent, and is generally associated with lower winter sea-ice concentrations (Jacobs 1991).

The ASC is driven by the sharp sub-surface horizontal gradient in temperature and salinity known as the Antarctic Slope Front (Ainley & Jacobs 1981). The ASF separates offshore warmer and more saline modified CDW (MCDW) from the colder and generally fresher Antarctic shelf waters, and is an important physical, chemical and biological feature (Jacobs 1991). In some regions the temperature difference may be as great as 3°C over 25 km. Where the ASF does not exist, such as on the Western Antarctic Peninsula in the Bellingshausen Sea, warm MCDW directly floods the continental slope and shelf, meaning that changes in CDW characteristics may have direct consequences for ice shelf basal melting in this region (Rignot & Jacobs 2002).

The transport of MCDW across the ASF onto the shelf is important for the formation of AABW, while the opposing transport of shelf water into the open ocean is important for the production of MCDW. Export of shelf water offshore also introduces nutrient rich surface waters from the continental shelf into the pelagic zone and can influence chlorophyll, zooplankton and higher predator distributions (Cottin *et al.* 2012). This mixing therefore has significant implications for biological and oceanographic properties, but the exact location and mechanisms for such mixing, including mesoscale eddy and tidal mixing, remain the subject of ongoing study. As the ASF is often associated with the edge of the summer sea ice, its influence on chlorophyll distribution can be difficult to separate from that of the sea ice, but at least in some areas the ASF appears to separate the regions of high shelf chlorophyll from lower offshore values north of the marginal sea ice zone (Smith & Comiso 2008).

8.2. Sub-polar water masses

Whitworth *et al.* (1998) provide a comprehensive assessment of circumpolar water mass characteristics and distributions for the sub-polar regime. The surface layer of AASW is exchatnged more or less freely across the southern boundary of the ACC as well as the ASF. As it is exposed to a wide range of latitudes, underlying water masses, atmosphere and ice interactions, it has a wide characteristic range (Fig. 4).

Upwelled CDW may be modified by mixing with the overlying AASW or across the ASF to form MCDW. This is generally cooler and fresher than the local offshore CDW, although with a similar density. Various regional subtypes of MCDW exist, such as Weddell Warm Deep Water (Gordon 1998) and Ross Sea MCDW (Orsi & Wiederwohl 2009). MCDW is generally found on the northern side of the ASF, but in certain regions and times it may penetrate onto the continental shelf and influence the melting of sea ice and ice shelves, as well as the formation of dense shelf water masses (Bindoff *et al.* 2001, Rignot & Jacobs 2002). These deep water intrusions onto the shelf act to supply the surface layers with nutrients and trace elements (Sedwick *et al.* 2000), but may introduce temperature stress to benthic assemblages on the normally relatively temperature invariant shelf sea floor (Barnes *et al.* 2006). The relatively warm MCDW below the winter mixed layer has been suggested as a possible overwintering zone for pelagic fauna, and is targeted in the Ross Sea by elephant seals (Biuw *et al.* 2007).

Over the continental shelf extremely dense water is formed in autumn and winter by a combination of ice formation, brine rejection, winds and heat loss. This water is known as shelf water (SW), and is significantly colder and more saline than MCDW. In certain regions around the continent SW may escape off the continental shelf, and if sufficiently dense relative to the ambient offshelf MCDW, sink to abyssal depths within the basins adjacent to Antarctica. As it escapes from the continental shelf the SW mixes with the overlying MCDW, becoming warmer and less saline and forming AABW (Fig. 4b). The specific mechanisms that form AABW vary around the Antarctic, but in all cases the production of extremely dense, saline SW is a critical first step and is often achieved in polynya regions. Intense brine rejection and heat loss within a polynya produces water at the surface freezing point with high salinity.

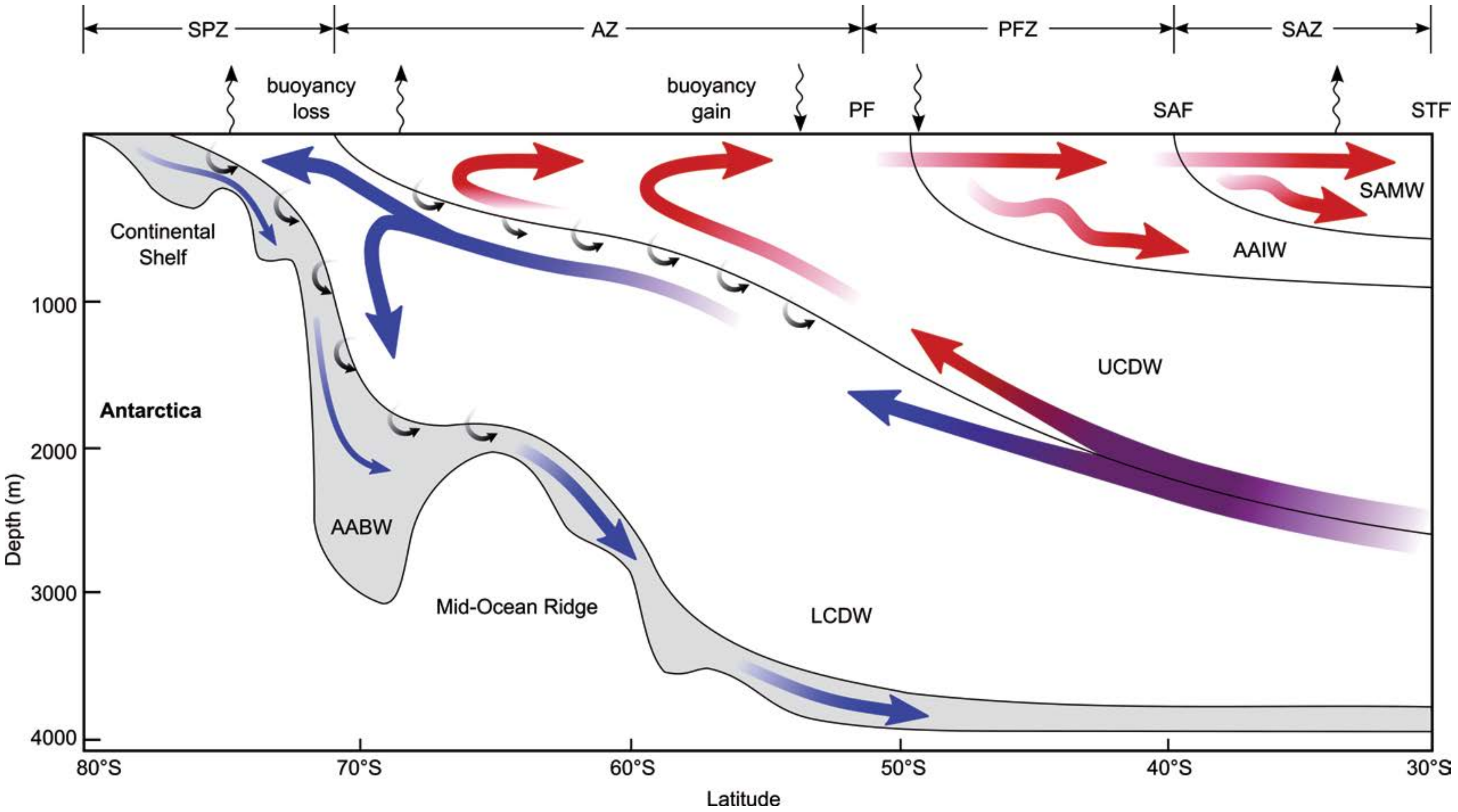


Figure 3 Schematic view of the meridional overturning circulation of the Southern Ocean, adapted from Speer *et al.* (2000). STF, Sub-Tropical Front; SAF, Sub-Antarctic Front; PF, Polar Front; SAMW, Sub-Antarctic Mode Water; AAIW, Antarctic Intermediate Water; UCDW, Upper Circumpolar Deep Water; LCDW, Lower Circumpolar Deep Water; AABW, Antarctic Bottom Water; SAZ, Sub-Antarctic Zone; PFZ, Polar Frontal Zone; AZ, Antarctic Zone; SPZ, Sub-Polar Zone. Arrows indicate mean flow direction. Red arrows show the upper cell and blue shows the deep cell. Small arrows indicate diabatic transport due to interior mixing. Note that this is an averaged view of the emergent residual flow due to complex, time-varying, three-dimensional processes and does not reflect the current directions of any given section across the ACC.

This rapidly overturns, filling the polynya region with a homogeneous mass of SW. In the Ross and Weddell Seas, SW typically forms at several polynya sites and is subsequently exported by the ACoC to fill the wide continental shelf seas (Orsi & Wiederwohl 2009); see Map 9. Where the SW encounters the ASC, eddy (Nøst *et al.* 2011) and tidal (Padman *et al.* 2002) processes lead to import and export across the shelf break on the western and central shelf, enabling SW to escape down the continental slope, mixing with the local MCDW and forming AABW (Whitworth & Orsi 2006). Broad continental shelves do not exist in the East Antarctic region, and so AABW forms only in a few discrete locations around the coastline (Map 9). These regions, which include the Adélie Depression on the George V shelf, and Cape Darnley, have strong polynyas in combination with a deep bathymetric shelf depression. Newly formed SW accumulates in the depressions rather than being exported and mixed away by the ACoC/ASC. The dense SW eventually overflows down the continental slope through isolated sills. The presence of bathymetric canyons leading down the continental slope in both of these regions may reduce the mixing of the dense plumes with the overlying MCDW, allowing the newly formed AABW to be exported to abyssal depths (Williams *et al.* 2010). The precise pathways of the nutrient and particulate rich AABW down the continental slope have been shown to impact local benthic assemblages, with dramatic differences in closely spaced regions apparently associated with the presence of AABW (Post *et al.* 2010). AABW exported from the Antarctic shelf forms the densest large water mass of the global ocean and circulates around all ocean basins, as far afield as the North Pacific (Map 9). Because AABW is formed near the surface it plays an important role in maintaining the ventilation of the deep ocean, transporting atmospheric gases, including oxygen, anthropogenic CO_2, surface nutrients and trace elements into the abyssal ocean. This is subsequently mixed vertically into the overlying deep waters, acting to renew the ocean interior (Marshal & Speer 2012).

9. The Southern Ocean mixed layer and surface properties

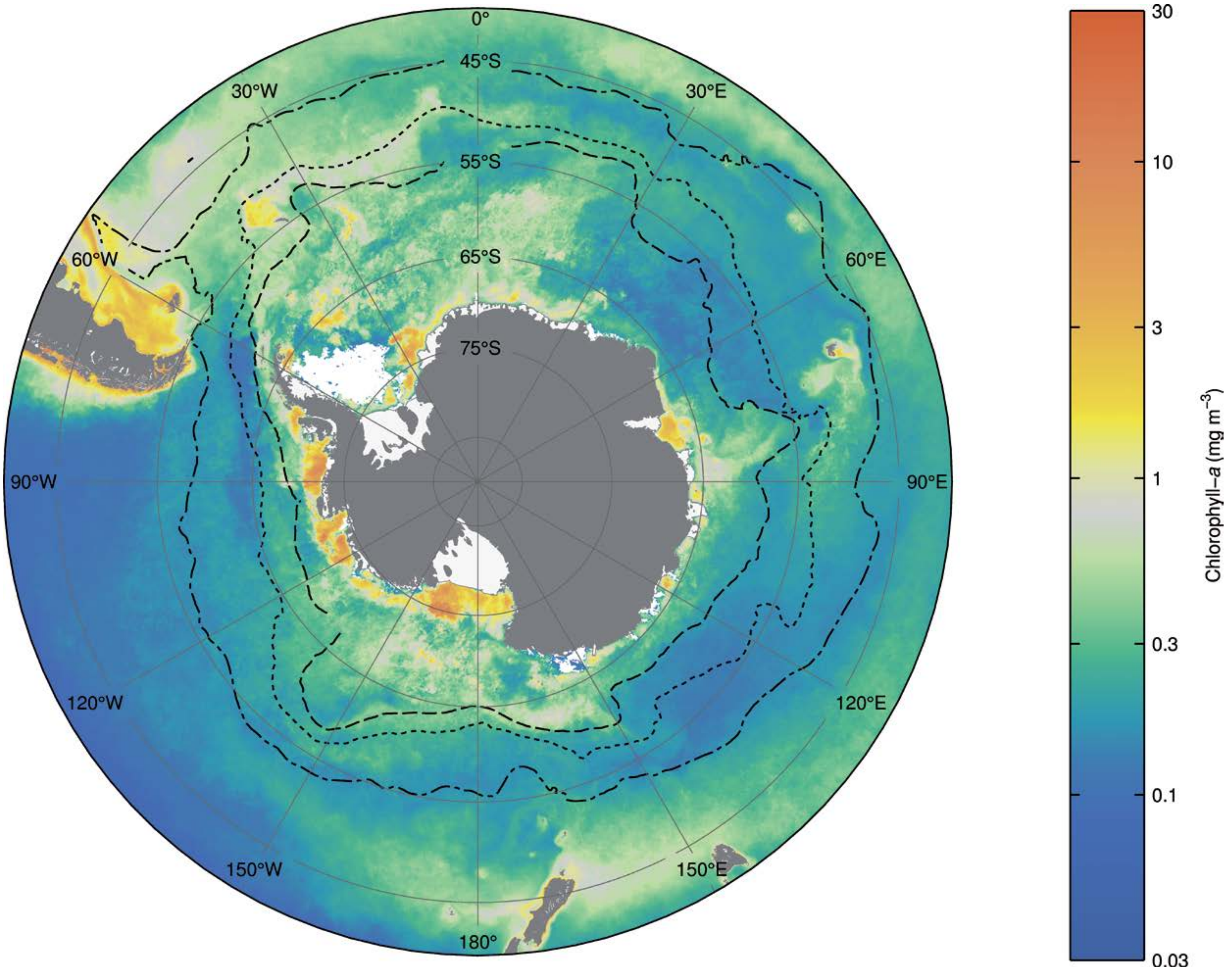
9.1. The mixed layer

The mixed layer of the Southern Ocean refers to the layer of water at the surface of the ocean with relatively homogeneous properties, separated from deeper layers by a sharp vertical gradient in temperature (thermocline) or density (pycnocline). The depth of the mixed layer is set by numerous factors: the strength of surface winds and heat and freshwater fluxes that act to vertically mix and homogenise the mixed layer, the divergence/convergence of winds acting to pump the vertical layers up or down, the lateral flux of heat and freshwater through current advection or eddy stirring, and the background vertical stratification. The mixed layer is further subdivided into the summer and winter mixed layers by the seasonal thermo/pycnocline (see subpanels in Fig. 4b), which deepens to include the entire mixed layer during winter, and grows downwards in summer as the surface is warmed and/or freshened by sea ice melt (Meijers *et al.* 2011).

Map 10 shows the Southern Ocean mixed layer depth from Argo observations for both summer and winter (Sallée *et al.* 2010). The greatest mixed layer depths of over 500 m occur in the northern ACC during winter, particularly north of the SAF where the thick SAMW winter mixed layer forms on the northern side of the steeply sloping isopycnals. The formation of this deep mixed layer and SAMW is driven by a combination of the overall circulation pattern, wintertime buoyancy loss, stronger winds, enhanced cold Ekman fluxes (Rintoul & England 2002), summertime stratification preconditioning (Sloyan *et al.* 2010) and upwelling (Dong *et al.* 2008). These forcing factors conspire to drive deep mixed layers and consequently SAMW formation in the eastern Indian Ocean, south of Australia, and in the south east Pacific. This contrasts with the summertime when mixed layer depths rarely exceed 150 m. These values are highly variable and interannual mixed layer depth standard deviations may be 20 m in the summer, and up to 60 m in winter (Sallée *et al.* 2010). There is also great spatial variability, both meridionally and zonally.

Meridional differences in mixed layer depth have strong consequences for primary productivity in the surface layer. The generally deeper mixed layers north of the PF limit light availability (Mitchell *et al.* 1991), and the micronutrient rich UCDW is well below the base of the mixed layer, leading to iron limited conditions (Boyd *et al.* 2000). In the sub-polar zone the annual mixed layer evolution is complicated by the presence of seasonal sea ice. In the summer time the freshwater input from the melting of sea ice, combined with warmer air temperatures and increased short wave radiation act to create a thin surface layer of AASW. In the marginal sea ice zone this summer mixed layer is of particular biological importance, because it increases water column stability and retains phytoplankton in the photic zone, as well as containing enhanced nutrient and iron availability due to sea-ice melt (Smith & Nelson 1986, Sedwick *et al.* 2000). It contributes significantly to the spring phytoplankton blooms, and Williams *et al.* (2008) demonstrate that delayed summer mixed layer development due to persistent sea ice has a significant negative impact on the overall productivity of the marine ecosystem over the Antarctic shelf.

The winter mixed layer forms by convection, driven initially by atmospheric cooling of the surface summer mixed layer and then by the brine rejection that occurs with sea ice formation. Over the continental shelf, in regions of sufficient sea ice formation, the winter mixed layer may extend to the seafloor (Williams *et al.* 2011) at just above the surface freezing temperature of -1.9°C. North of the shelf break, the presence of the MCDW temperature maxima immediately below the base of the winter mixed layer may complicate the seasonal



Environmental Setting Map 8 Summer near-surface chlorophyll-*a* from MODIS Aqua satellite estimates (Feldman & McClain 2010). Climatology spans the 2002/03 to 2009/10 austral summer seasons. White indicates areas of missing data due to ice shelves or sea ice cover. The dashed line shows the southern Antarctic Circumpolar Current front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).

evolution of the mixed layer. If ice formation is strong it may quickly remove the buoyancy barrier formed by the summer mixed layer, allowing mixing to the base of the winter mixed layer. This in turn allows the warm water from below the winter mixed layer to convect into the mixed layer, increasing the temperature and feeding back on the formation of sea ice (Martinson 1990). In some regions, such as in the western Weddell Sea, the T_{max} layer may be quite deep, inhibiting any warming of the winter mixed layer and allowing persistent sea ice, while in other regions the shallow winter mixed layer and warming from below may reduce ice thickness and coverage (Gordon & Huber 1990, Gordon 1998). Significant seasonal variability may occur in both the mixed layer depth and sea ice cover in some regions.

9.2. Sea surface temperature and salinity

The temperature and salinity structure of the Southern Ocean mixed layer shows strong spatial — and to a lesser extent, temporal — variation. Map 11 shows the sea surface temperature (SST) of the Southern Ocean for summer and winter. Winter SST is relatively constant at near freezing temperatures in the sub-polar regime south of the ACC. North of the ACC, SST increases in relatively sharp steps associated with the PF, SAF and STF, where it exceeds 12°C. The path of the ACC influences the SST, and the SST minimum is found in the vicinity of the south east Pacific where the ACC is at its southernmost point. It then diverts equatorwards and warms in the Atlantic sector before moving polewards again in the Indian and Pacific sectors and becoming cooler and fresher (Sun & Watts 2002). South of the southern boundary, cooler waters are found in the Ross and Weddell gyres, as cold coastal waters are circulated northwards. The presence of persistent sea ice means that the annual temperature range in the gyres is low (Barnes *et al.* 2006), while over most of the ACC it is around 2–3°C. The strongest seasonal variability south of the ACC occurs in the Western Antarctic Peninsula area, which has also been identified as a region of strong SST warming (>1°C) over the last 50 years (Meredith & King 2005). Montes-Hugo *et al.* (2009) show a decrease of 12% in chlorophyll in the Western Antarctic Peninsula area, possibly linked to the trend in SST.

The SST itself is governed by the heat content of the mixed layer, which is in turn controlled by several factors, including the mixed layer depth, strength of vertical and lateral mixing, horizontal advection by Ekman and geostrophic flows, and the exchange of latent and sensible heat with the atmosphere (Dong *et al.* 2007). On interseasonal timescales the SST responds most strongly to changes in the surface heat flux, but changes in Ekman advection and mixed layer depth due to seasonal winds are also significant. The surface winds also respond strongly to the SST, resulting in complex feedback processes (O'Neill *et al.* 2005). On shorter timescales the variability of the SST is primarily driven by changes in wind stress, notably the Southern Annular Mode, which acts to modify the mixed layer depth, upwell/downwell water masses and enhance Ekman transport. A positive Southern Annular Mode generates negative SST anomalies in the AZ and PFZ, while north of the ACC it tends to increase SST (Lovenduski & Gruber 2005).

Due to the relatively low temperatures found in the Southern Ocean mixed layer, particularly south of the PF, the sea surface salinity plays an important role in setting the mixed layer depth. The estimated mixed layer depth can vary by several hundred metres, depending on whether a temperature or (more properly) density based criterion is used (Dong *et al.* 2008), so it is particularly important to use a density criterion in this region. This variation is most apparent over the continental shelf where brine rejection drives the formation of extremely dense shelf water and basal melt from ice shelves acts to freshen it. Salinity is also important for water column stability in the AZ because upwelling CDW causes a sub-surface temperature inversion, while the vertical salinity profile acts to stabilise the water column. Basin scale observations of evaporation and precipitation over the Southern Ocean are difficult to obtain, and the net surface freshwater flux and variability is poorly known, even in reanalysis products, so the impact of these factors on surface water properties is difficult to account for at a broad scale.

10. Seafloor temperature

The Antarctic seabed has traditionally been regarded as cold and thermally stable, with little spatial or seasonal variation in temperature. However, there are marked spatial variations in continental shelf seabed temperature around Antarctica (Clarke *et al.* 2009). The most notable of these is the striking difference between the thermal environment of the continental shelf seabed to the west of the Antarctic Peninsula, and that of the shelves around continental Antarctica (Map 12). The western Antarctic Peninsula shelf is significantly warmer (warmer than 0°C) than shelves around continental Antarctica. This is a result of flooding of the shelf by Circumpolar Deep Water from the Antarctic Circumpolar Current. Bransfield Strait is an exception, containing cold Weddell Sea bottom water. The coldest shelf seabed temperatures (0 to -2°C) are in the Weddell Sea, Ross Sea, and Prydz Bay and are associated with the formation of dense, cold Antarctic Bottom Water (AABW; see sub-polar water masses, above). Furthermore, the deep waters of the Weddell Sea shelf are also strongly influenced by very cold water produced by interaction of shelf water with the underside of floating ice shelves (Weiss *et al.* 1979). AABW can descend down the adjacent slope to inject cold water into the Southern Ocean deep sea. Deep sea seabed temperatures are coldest in the Weddell Sea and are progressively warmer to the east. There is a distinct latitudinal gradient in the difference between seabed temperatures on the shelf and in the deep sea, with the deep sea warmer by up to ~2°C at high latitudes and colder by ~2°C around sub-Antarctic islands.

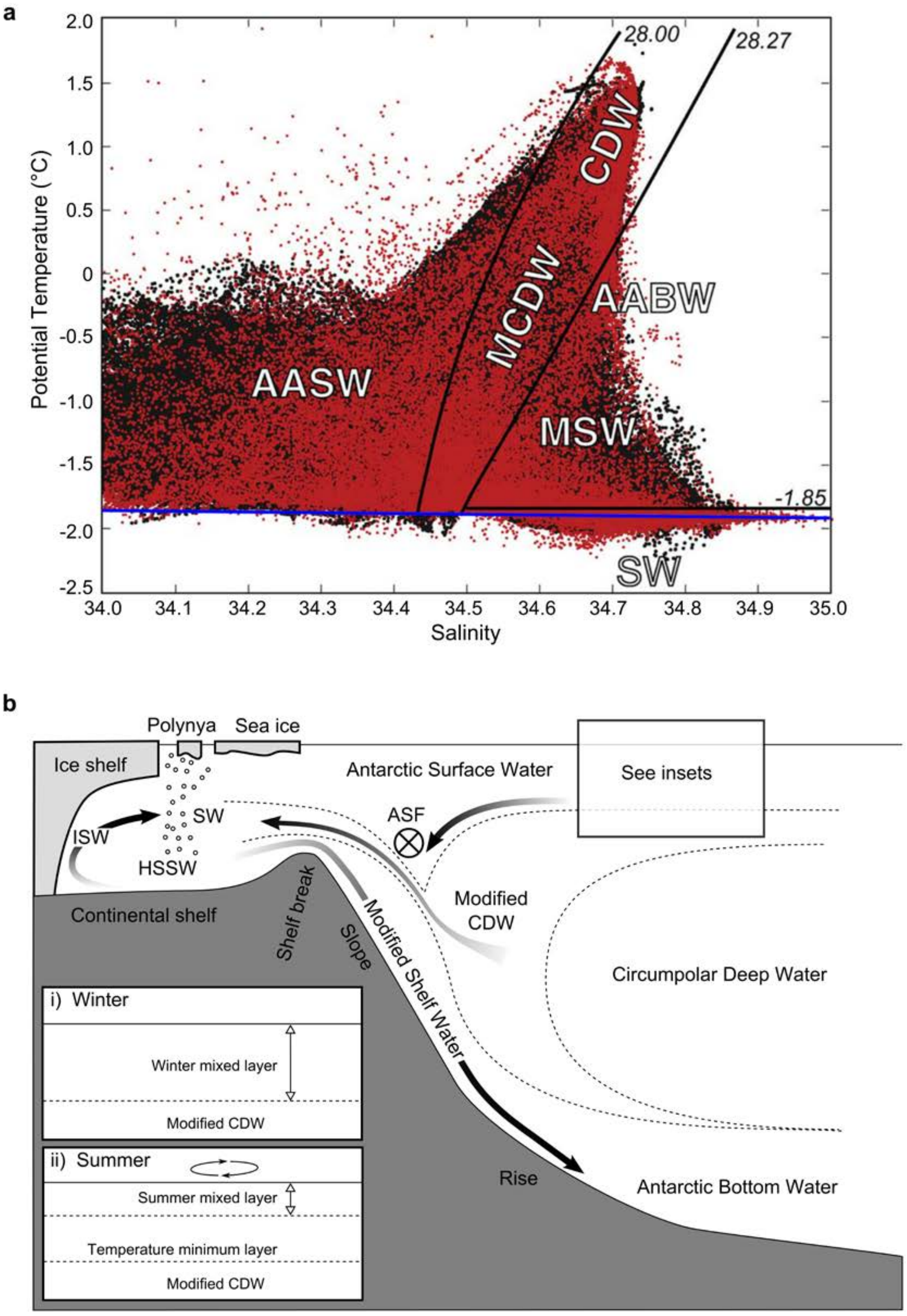


Figure 4 (a) Ross Sea water mass temperature and salinity characteristics for depths shallower than 2000 m. Solid lines show the 28.00 and 28.27 kgm^{-3} neutral density surfaces separating Antarctic Surface Water, Modified Circumpolar Deep Water and Antarctic Bottom Water. The blue horizontal line shows the surface freezing point of seawater. Major water masses are labelled: Antarctic Surface Water (AASW), Modified Circumpolar Deep Water (MCDW/CDW), Modified Shelf Water (MSW/SW), and Antarctic Bottom Water (AABW). Reproduced from Orsi & Wiederwohl (2009). (b) Schematic of Antarctic continental margin water masses showing the typical East Antarctic spatial relationship between the Antarctic Slope Front (ASF), MCDW/CDW, SW, Ice Shelf Water (ISW), High Salinity Shelf Water (HSSW), AASW and AABW. Subpanels show the evolution of the summer and winter mixed layers. Adapted from Williams *et al.* (2008).

11. Surface and water column nutrients and oxygen

Large-scale nutrient and oxygen patterns in the world oceans are determined by the balance between biological impacts and ocean circulation (Sarmiento & Gruber 2006). Biological processes create a strong vertical nutrient gradient: primary production utilises nutrients in surface waters to form organic matter, a portion of which sinks to depth where it is remineralised, returning the nutrients to the water column. Oxygen, high in surface waters and depleted at depth, is generally negatively correlated with nutrients. At the surface, interaction with the atmosphere saturates waters with oxygen, while as water masses age and circulate, biological respiration consumes and depletes oxygen. Superimposed on these biologically-mediated vertical gradients of oxygen and nutrients is the global overturning circulation. The circulation carries oxygen-rich waters from surface to depth in subduction regions, and returns nutrients from depth to the surface, primarily in the upwelling gyres of the world oceans, and in particular within the Southern Ocean.

11.1. Nutrients: the circumpolar view

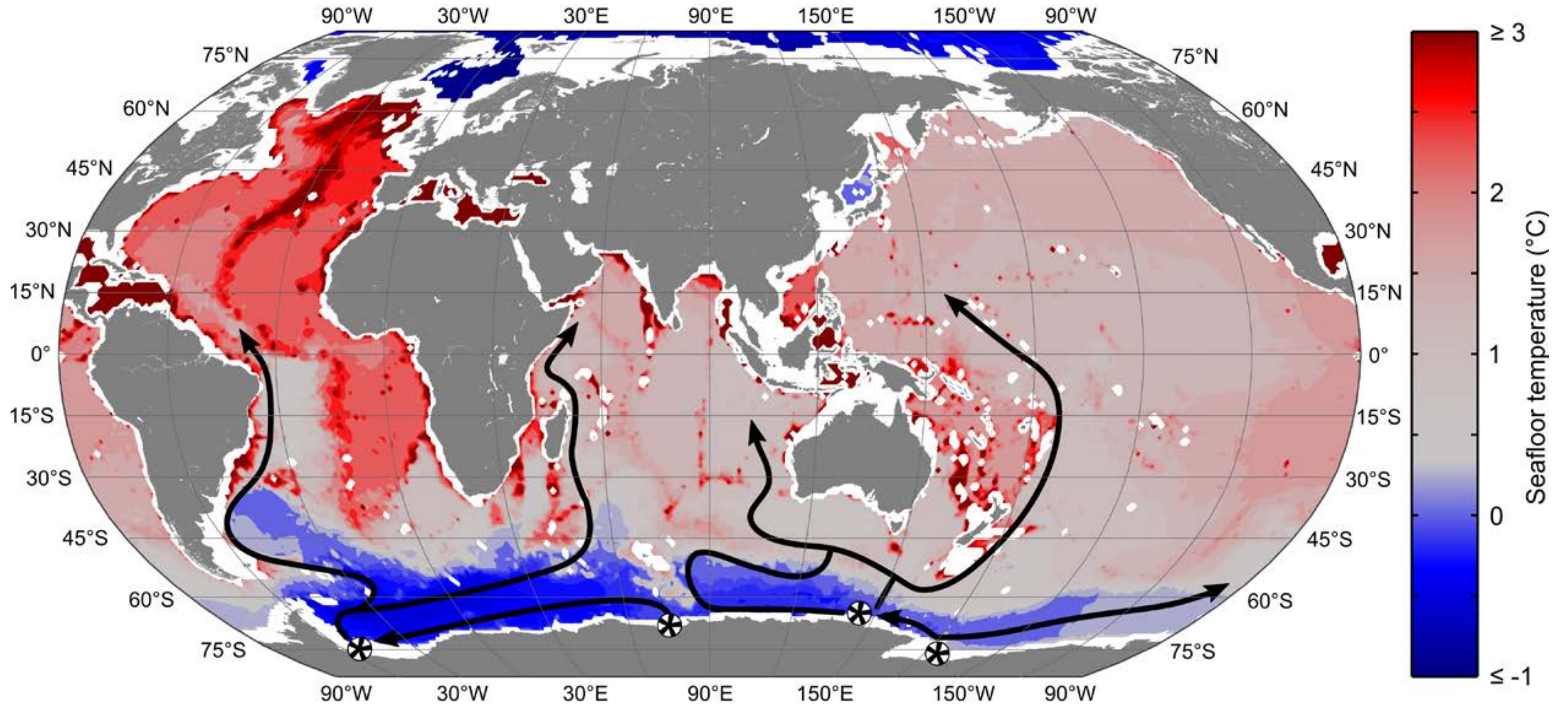
Dominant nutrient patterns in the Southern Ocean can be understood in this context of the global overturning circulation. The surface waters in the generally upwelling sub-polar gyre, south of the Antarctic Circumpolar Current (ACC), are rich in macronutrients: nitrate (NO_3^-), phosphate (PO_4^{3-}), and silicate (primarily $Si(OH)_4$). This region is often referred to as a high nutrient, low chlorophyll region because despite the highest concentrations of surface macronutrients found throughout the world oceans, the waters are not highly productive due to micronutrient (iron) and light limitations. South of and in the southern flanks of the ACC, silicate is stripped from surface waters by the diatom community, creating a maximum in silicate export to depth (Ito *et al.* 2005).

Waters north of, and in the northern ACC, get their nutrients largely from the horizontal Ekman advection of waters equatorward across the ACC (Pollard *et al.* 2006). These waters have the unique characteristic of being rich in nitrate and phosphate, but relatively depleted in silicate (Sarmiento *et al.* 2004). Light limitation eases at these lower latitudes, and iron becomes more available within the water column, in part from the ventilation of Upper Circumpolar Deep Water (UCDW) in the ACC, and in part from aeolian dust inputs. Nutrients in these waters support a circumpolar maximum in primary productivity, generally dominated by small phytoplankton (Ito *et al.* 2005), and limited by silicate (Hiscock *et al.* 2003).

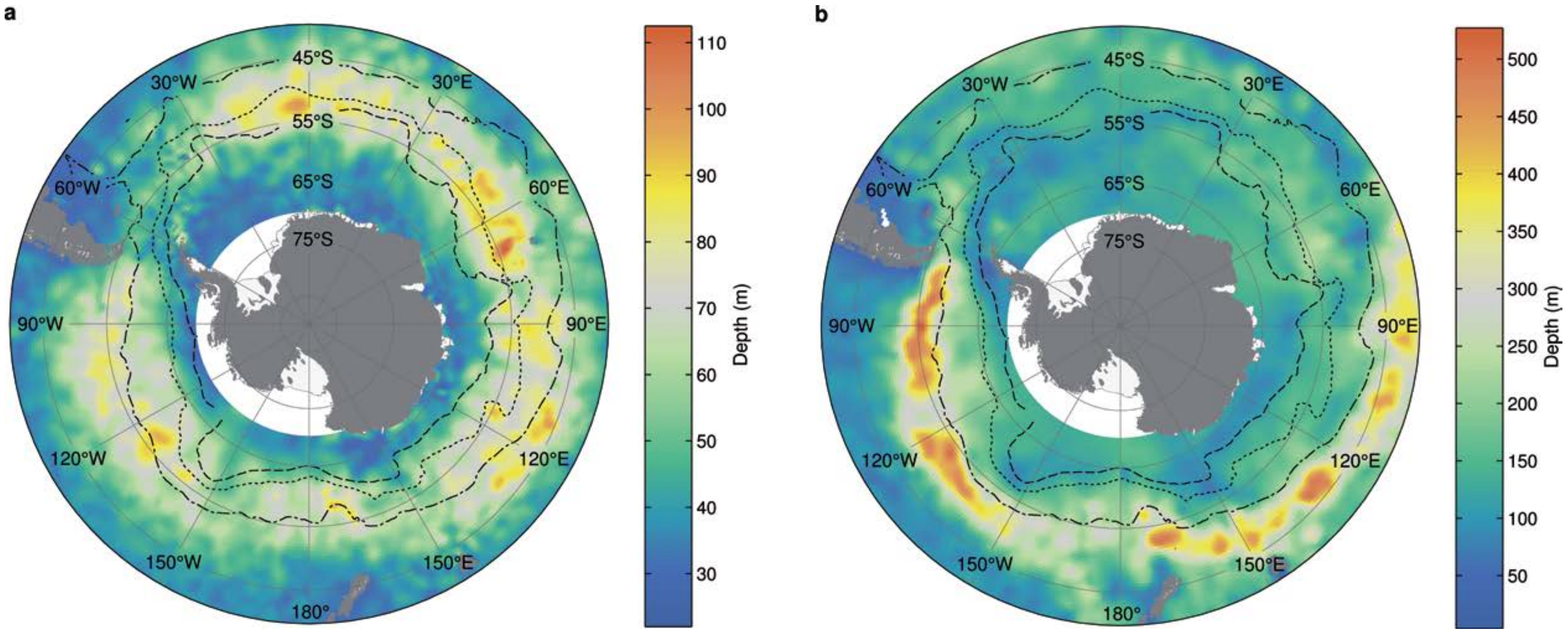
Fig. 5, showing cross-sections of nitrate and silicate concentrations, illustrates this circumpolar pattern of nutrients in the Southern Ocean. The phosphate distribution, not shown, is similar to the nitrate distribution. In the upwelling sub-polar gyre south of the southern ACC front (SACCF), nitrate, phosphate, and silicate concentrations are all high. Wind-driven horizontal Ekman transport carries these nutrients northwards across the ACC. Nitrate and phosphate concentrations are thus high as far north as the northern ACC boundary (indicated by the SAF). Silicate, however, is depleted on the southern edge of the ACC, and thus has very low values in surface waters north of this region. North of the ACC waters in the sub-tropical gyres, all macronutrient values are low.

11.2. Nutrients: zonal heterogeneity

Whereas this circumpolar view provides a good description of the dominant patterns of nutrients in the Southern Ocean, superimposed upon this view is a significant degree of zonal heterogeneity. This can be seen in Map 13, showing nitrate and silicate concentrations at the surface. The spatial heterogeneity has many causes, including mesoscale eddies transporting volume (and thus nutrient properties) southward across the ACC (Palter *et al.* 2010), spatially-variable aeolian iron inputs, and interactions of the ACC with bathymetry.



Environmental Setting Map 9 Antarctic Bottom Water (AABW) production (shown by stars) and generalised circulation pathways. Colour scale shows World Ocean Atlas bottom temperatures, with cold AABW circulating with the ACC and spreading northwards into each ocean basin. Schematic pathways adapted from Purkey & Johnson (2012).



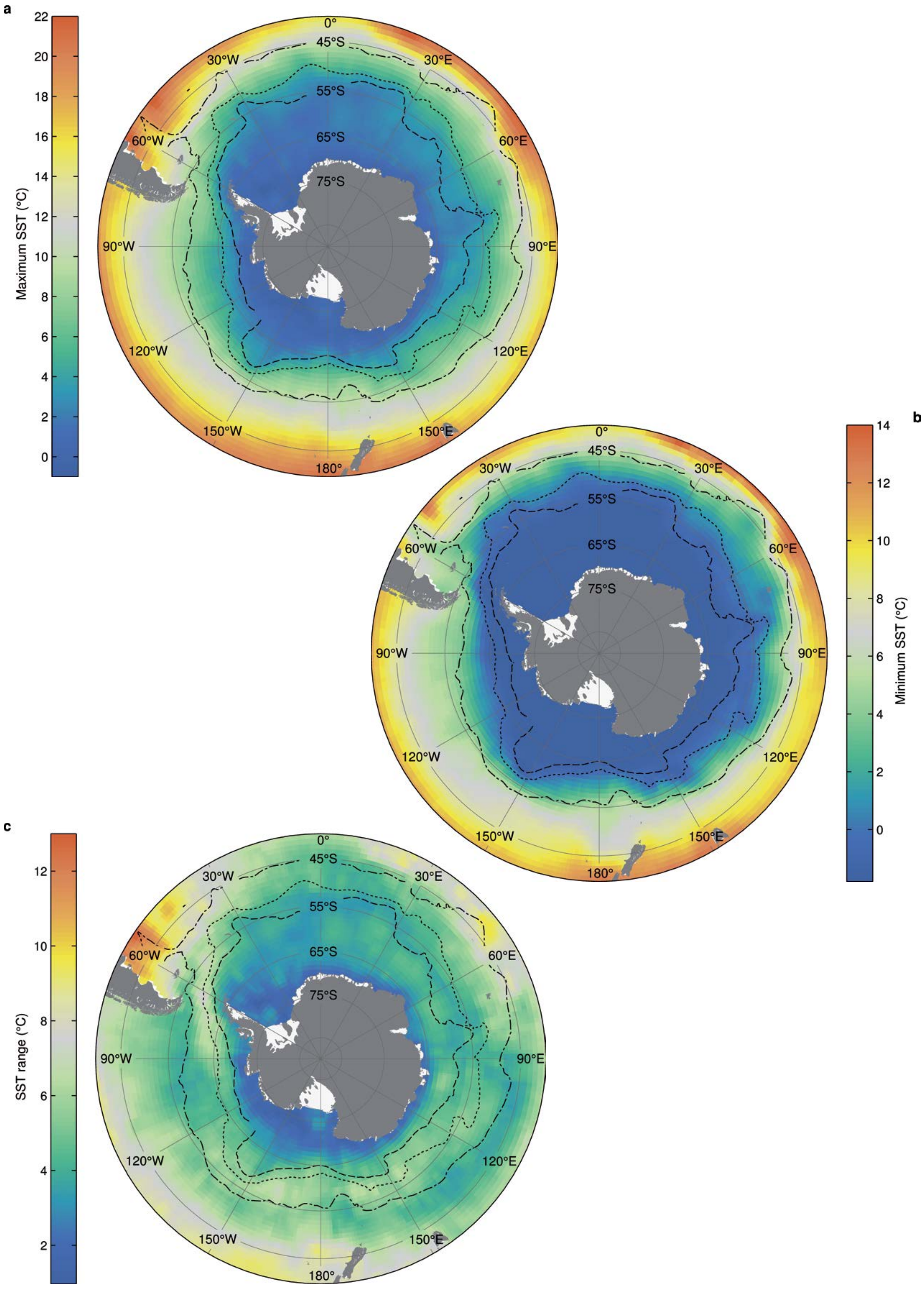
Environmental Setting Map 10 Mixed layer depth calculated from Argo floats for (a) summer (Jan/Feb); (b) winter (Aug/Sep) using a vertical density difference based criterion of 0.03 kgm^{-3} from the surface value. Note the winter evolution of deep mixed layer depths north of the Antarctic Circumpolar Current in the Indian and Pacific sectors. Data provided by J.-B. Sallée. The dashed line shows the southern Antarctic Circumpolar Current front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).

Both macro- and micro-nutrient concentrations are likely elevated downstream of topographical features, as suggested by persistently elevated chlorophyll in these areas (Boyd 2002, Sokolov & Rintoul 2007). Flow across shallow plateaus may cause sediment resuspension and associated release of iron (e.g. Chever *et al.* 2010), while Sokolov & Rintoul (2007) used model data to show that interaction of large topographical features with the ACC drives upwelling. The locations of the upwelling maxima, and thus the implied areas of high surface nutrients, are associated with the major bathymetric features including: the Pacific-Antarctic Ridge, the East Pacific Rise, the Drake Passage, the Scotia Sea, the Mid-Atlantic Ridge near 0°E, the Conrad Rise and Crozet Plateau near 45°E, the Kerguelen Plateau, and the Southeast Indian Ridge near 145°E (Map 8). These regions of high nutrients and elevated chlorophyll may be important for higher trophic level biota as well.

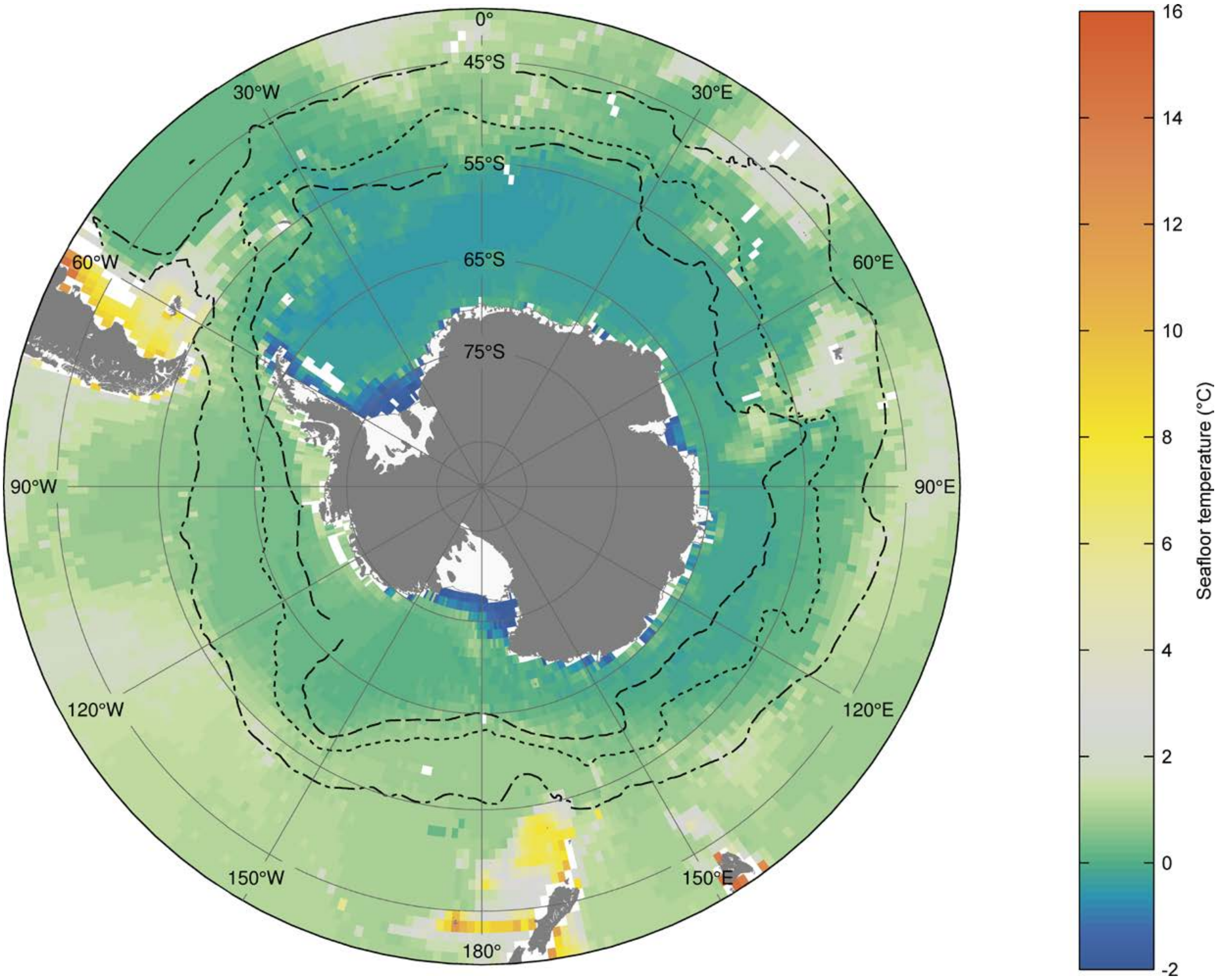
11.3. Oxygen and temporal change

Oxygen is a key tracer of the meridional circulation (Fig. 6). The oxygen low (parallel to the 27.6 kgm^{-3} density surface) is the upwelling limb of Circumpolar Deep Water. This water has been away from the surface for the longest time. The oxygen rich waters above are saturated surface waters, with oxygen content increasing as temperature decreases. To the north (approximately parallel to the 26.8 kgm^{-3} density surface) is a region of relatively thick, high oxygen waters (Sub-Antarctic Mode Water) indicating that these waters have interacted with the surface ocean relatively recently. Beneath the oxygen minimum layer, oxygen concentrations increase and reach a maximum nearest to Antarctica, reflecting an Antarctic source for these waters.

Sub-surface measurements of oxygen are sufficiently comprehensive (relative to other biologically active variables) that it is possible to assess temporal changes within the water column for the Southern Ocean (Aoki *et al.* 2005, Helm *et al.* 2011). Comparing all available Southern Ocean oxygen profiles centred on 1970 with oxygen profiles from the World Ocean Circulation Experiment (1990s) shows widespread decreases in oxygen concentration in the upper ocean (Fig. 7). The largest oxygen decreases are in the Southern Ocean and are circumpolar in extent (Helm *et al.* 2011). These high-latitude oxygen decreases extend throughout the water column. The Southern Ocean represents 25% of this decrease in the global average of the oxygen concentration over the upper 1000 m. The implication is that the signal of oxygen change is largely driven by changes in air-sea interaction rather than by internal readjustment of ocean properties. The Southern Ocean decrease includes both the upwelling Circumpolar Deep Waters and the relatively young Antarctic Intermediate Water and Sub-Antarctic Mode Water density layers (27.4 to 26.8 kgm^{-3}). Similar decreases occur in ocean biogeochemical models (Matear & Hirst 2003, Hofmann & Schellnhuber 2009) and in these models most of the oxygen decrease in the Southern Ocean is related to increased stratification of the upper ocean and reduced ventilation from the surface. These results highlight the fact that changes are already occurring in the global carbon cycle (Helm *et al.* 2011), with significant implications for nutrient distributions, ocean acidification, and ultimately the diversity and distribution of marine biota (see chapter 9).



Environmental Setting Map 11 Remotely sensed mean sea surface temperature (SST) between 1981 and 2005 for (a) summer maxima; (b) winter minima; (c) the difference between the two. Adapted from Barnes *et al*. (2006). The dashed line shows the Southern Antarctic Circumpolar Current Front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).



Environmental Setting Map 12 Mean annual seafloor temperatures derived from World Ocean Atlas 2005 data (Clarke *et al.* 2009). These data emphasise the colder temperatures on continental shelves in the vicinity of ice shelves, and the warmer temperatures of abyssal water in an eastward (clockwise) direction from the Antarctic Peninsula. White indicates areas of insufficient sample coverage. The dashed line shows the southern Antarctic Circumpolar Current front, the dotted line the Polar Front, and the dash-dotted line the Sub-Antarctic Front (mean front positions from Sokolov & Rintoul 2009).

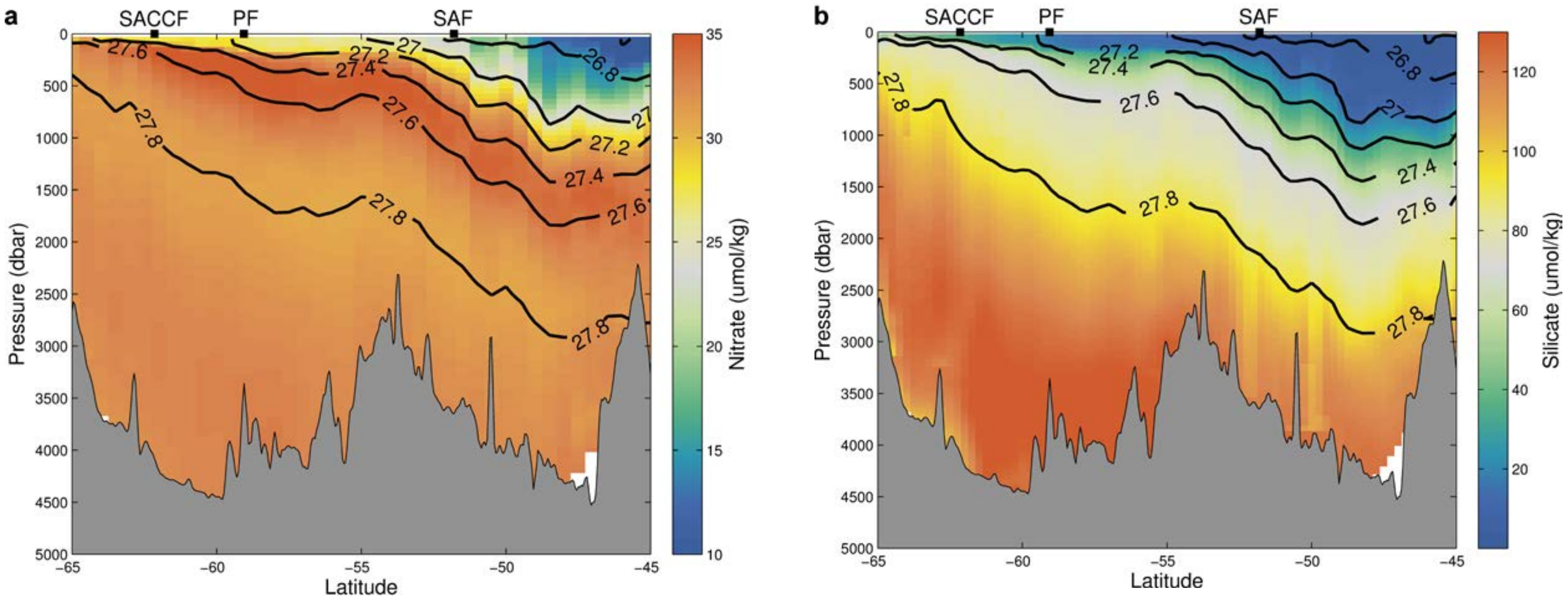
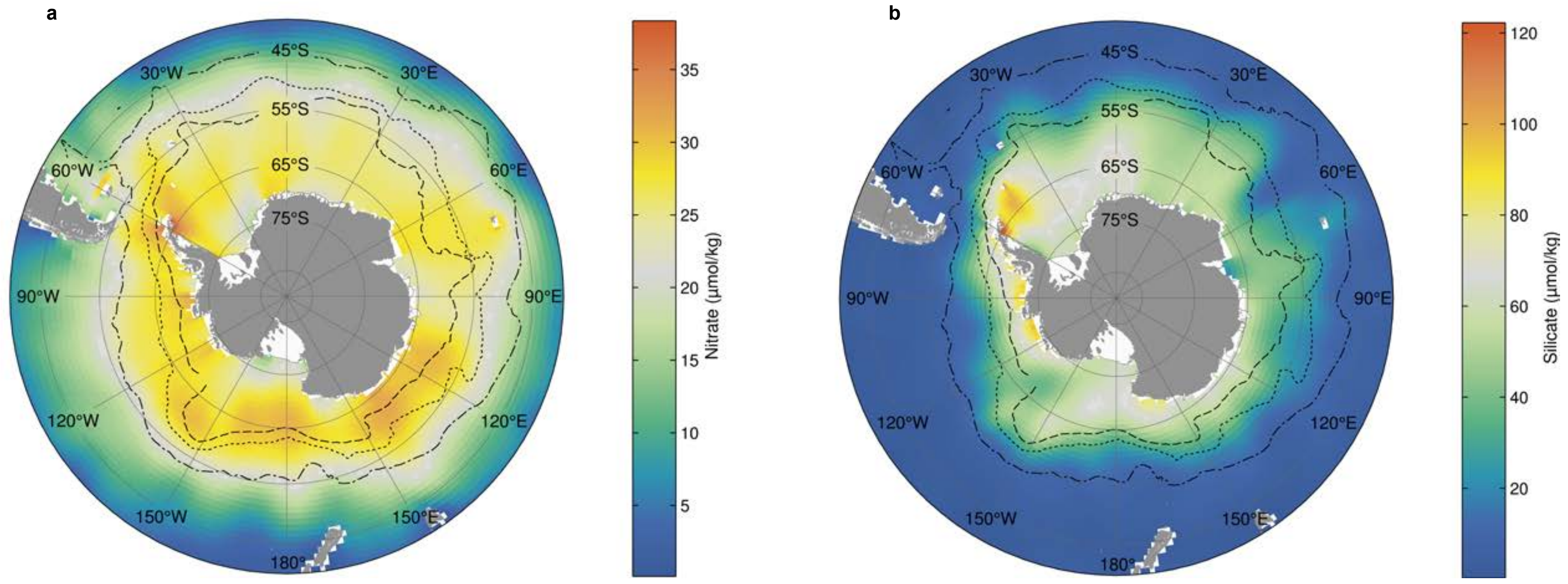


Figure 5 Cross-sections of (a) nitrate; (b) silicate along the SR03 line south of Tasmania in spring 2001 (data from Tilbrook *et al.* 2001). Three fronts, representing three main cores of the Antarctic Circumpolar Current, are shown from south to north: the southern ACC Front (SACCF), the Polar Front (PF), and the Sub-Antarctic Front (SAF) (Sokolov & Rintoul 2009). Density contours (σ_θ) are overlain to show gyre structure.



Environmental Setting Map 13 Climatological winter surface (a) nitrate; (b) silicate (data from the World Ocean Atlas 2009; Garcia *et al.* 2010). The three main Antarctic Circumpolar Current fronts are overlain: SACCF (dashed line), PF (dotted), and SAF (dash-dotted). The Southern Ocean has the highest nitrate and silicate concentrations found in the world's oceans. The high nitrate values extend to the northern edge of the ACC (marked by the SAF), whereas the high silicate only extends as far north as the southern edge of the ACC (marked by the SACCF).

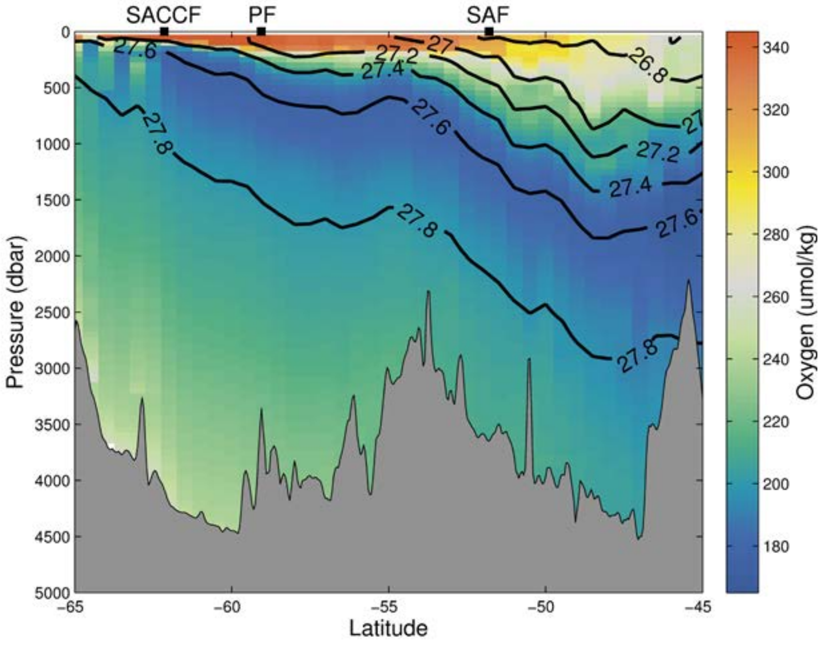


Figure 6 Cross-sections of oxygen along the SR03 line south of Tasmania in spring 2001 (data from Tilbrook *et al.* 2001). Three fronts, representing three main cores of the Antarctic Circumpolar Current, are shown from south to north: the Southern ACC Front (SACCF), the Polar Front (PF), and the Sub-Antarctic Front (SAF) (Sokolov & Rintoul 2009). Density contours (σ_θ) are overlain to show gyre structure.

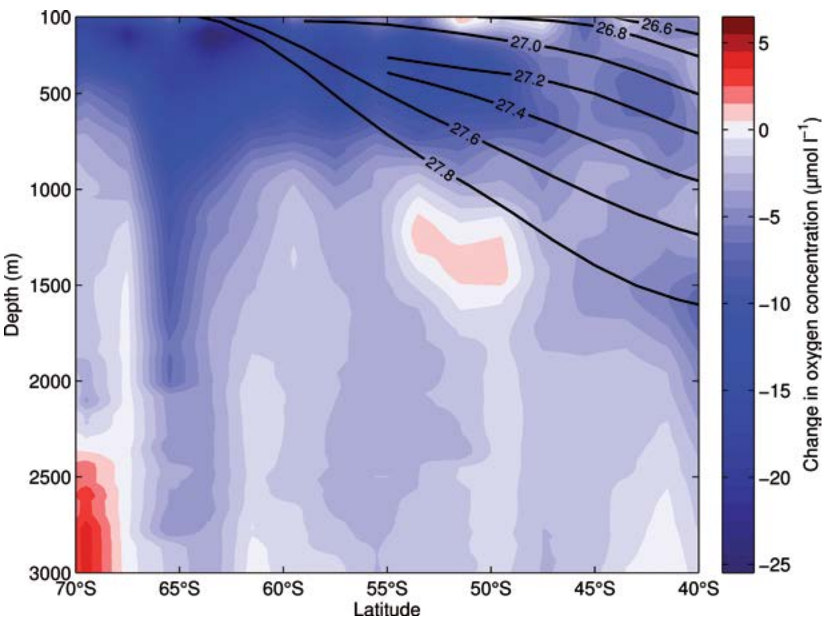


Figure 7 Zonally-averaged oxygen changes over depth, from ~1970 to 1992. Red represents increases in oxygen concentration over time, while blue represents decreases. Density contours (σ_θ) are overlain.

12. Conclusions

The physical environment of the Antarctic margin and Southern Ocean is highly dynamic on both spatial and temporal scales. On geological time scales, entire habitats on the continental shelf have been repeatedly destroyed by the advance of glaciers during glacial maxima, with only a few small regions potentially remaining ice-free during the last glaciation. These glacial advances are strongly imprinted on the morphology of the Antarctic shelf, with the resulting deep shelf basins contrasting with adjacent shallow banks that were bypassed by glacial streams. Depth on the shelf is also significant for seabed disturbance, with shallow regions affected by anchor ice and large parts of the shelf frequently scoured by icebergs. Sea ice plays an important role in Southern Ocean biogeochemical cycles and Antarctic marine ecosystem function. Ice-associated primary production contributes significantly to the overall biological production of the ice-covered parts of the Southern Ocean, with meltwater stratification, and nutrient and algae release triggering ice-edge blooms during spring and summer. Additionally, the seasonal cycle is strongly imprinted on light levels and temperature, while spatial variability in temperature is driven by the physical oceanography. Large changes in temperature, as well as nutrients, occur across the Antarctic Circumpolar Current. This powerful current separates sub-tropical from sub-polar water masses, which are distinct in their physical, chemical and biological properties. Within these water masses, nutrient levels are also modulated by biological processes, resulting in strong vertical gradients. The marine biota of the Southern Ocean and Antarctic margin has evolved to not only survive, but to thrive in these extremely harsh environments. The resulting fauna and flora is rich, diverse and highly resilient to the dynamics of this environment.

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

Scope

Biogeographic information is of fundamental importance for discovering marine biodiversity hotspots, detecting and understanding impacts of environmental changes, predicting future distributions, monitoring biodiversity, or supporting conservation and sustainable management strategies.

The recent extensive exploration and assessment of biodiversity by the Census of Antarctic Marine Life (CAML), and the intense compilation and validation efforts of Southern Ocean biogeographic data by the SCAR Marine Biodiversity Information Network (SCAR-MarBIN / OBIS) provided a unique opportunity to assess and synthesise the current knowledge on Southern Ocean biogeography.

The scope of the Biogeographic Atlas of the Southern Ocean is to present a concise synopsis of the present state of knowledge of the distributional patterns of the major benthic and pelagic taxa and of the key communities, in the light of biotic and abiotic factors operating within an evolutionary framework. Each chapter has been written by the most pertinent experts in their field, relying on vastly improved occurrence datasets from recent decades, as well as on new insights provided by molecular and phylogeographic approaches, and new methods of analysis, visualisation, modelling and prediction of biogeographic distributions.

A dynamic online version of the Biogeographic Atlas will be hosted on www.biodiversity.aq.

The Census of Antarctic Marine Life (CAML)

CAML (www.caml.aq) was a 5-year project that aimed at assessing the nature, distribution and abundance of all living organisms of the Southern Ocean. In this time of environmental change, CAML provided a comprehensive baseline information on the Antarctic marine biodiversity as a sound benchmark against which future change can reliably be assessed. CAML was initiated in 2005 as the regional Antarctic project of the worldwide programme Census of Marine Life (2000-2010) and was the most important biology project of the International Polar Year 2007-2009.

The SCAR Marine Biodiversity Information Network (SCAR-MarBIN)

In close connection with CAML, SCAR-MarBIN (www.scarmarbin.be, integrated into www.biodiversity.aq) compiled and managed the historic, current and new information (i.a. generated by CAML) on Antarctic marine biodiversity by establishing and supporting a distributed system of interoperable databases, forming the Antarctic regional node of the Ocean Biogeographic Information System (OBIS, www.iobis.org), under the aegis of SCAR (Scientific Committee on Antarctic Research, www.scar.org). SCAR-MarBIN established a comprehensive register of Antarctic marine species and, with biodiversity.aq provided free access to more than 2.9 million Antarctic georeferenced biodiversity data, which allowed more than 60 million downloads.

The Editorial Team

Claude DE BROYER is a marine biologist at the Royal Belgian Institute of Natural Sciences in Brussels. His research interests cover structural and ecofunctional biodiversity and biogeography of crustaceans, and polar and deep sea benthic ecology. Active promoter of CAML and ANDEEP, he is the initiator of the SCAR Marine Biodiversity Information Network (SCAR-MarBIN). He took part to 19 polar expeditions.

Huw GRIFFITHS is a marine Biogeographer at the British Antarctic Survey. He created and manages SOMBASE, the Southern Ocean Mollusc Database. His interests include large-scale biogeographic and ecological patterns in space and time. His focus has been on molluscs, bryozoans, sponges and pycnogonids as model groups to investigate trends at high southern latitudes.

Cédric d'UDEKEM d'ACOZ is a research scientist at the Royal Belgian Institute of Natural Sciences, Brussels. His main research interests are systematics of amphipod crustaceans, especially of polar species and taxonomy of decapod crustaceans. He took part to 2 scientific expeditions to Antarctica on board of the *Polarstern* and to several sampling campaigns in Norway and Svalbard.

Bruno DANIS is an Associate Professor at the Université Libre de Bruxelles, where his research focuses on polar biodiversity. Former coordinator of the scarmarbin.be and antabif.be projects, he is a leading member of several international committees, such as OBIS or the SCAR Expert Group on Antarctic Biodiversity Informatics. He has published papers in various fields, including ecotoxicology, physiology, biodiversity informatics, polar biodiversity or information science.

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Falk HUETTMANN is a 'digital naturalist' he works on three poles (Arctic, Antarctic and Hindu-Kush Himalaya) and elsewhere (marine, terrestrial and atmosphere). He is based with the university of Alaska-Fairbank (UAF) and focuses primarily on effective conservation questions engaging predictions and open access data.

Philippe KOUBBI is professor at the University Pierre et Marie Curie (Paris, France) and a specialist in Antarctic fish ecology and biogeography. He is the Principal Investigator of projects supported by IPEV, the French Polar Institute. As a French representative to the CCAMLR Scientific Committee, his main input is on the proposal of Marine Protected Areas. His other field of research is on the ecoregionalisation of the high seas.

Ben RAYMOND is a computational ecologist and exploratory data analyst, working across a variety of Southern Ocean, Antarctic, and wider research projects. His areas of interest include ecosystem modelling, regionalisation and marine protected area selection, risk assessment, animal tracking, seabird ecology, complex systems, and remote sensed data analyses.

Anton VAN DE PUTTE works at the Royal Belgian Institute for Natural Sciences (Brussels, Belgium). He is an expert in the ecology and evolution of Antarctic fish and is currently the Science Officer for the Antarctic Biodiveristy Portal www.biodiversity.aq. This portal provides free and open access to Antarctic Marine and terrestrial biodiversity of the Antarctic and the Southern Ocean.

Bruno DAVID is CNRS director of research at the laboratory BIOGÉOSCIENCES, University of Burgundy. His works focus on evolution of living forms, with and more specifically on sea urchins. He authored a book and edited an extensive database on Antarctic echinoids. He is currently President of the scientific council of the Muséum National d'Histoire Naturelle (Paris), and Deputy Director at the CNRS Institute for Ecology and Environment.

Julian GUTT is a marine ecologist at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, and professor at the Oldenburg University, Germany. He participated in 13 scientific expeditions to the Antarctic and was twice chief scientist on board Polarstern. He is member of the SCAR committees ACCE and AnT-ERA (as chief officer). Main focii of his work are: biodiversity, ecosystem functioning and services, response of marine systems to climate change, non-invasive technologies, and outreach.

Graham HOSIE is Principal Research Scientist in zooplankton ecology at the Australian Antarctic Division. He founded the SCAR Southern Ocean Continuous Plankton Recorder Survey and is the Chief Officer of the SCAR Life Sciences Standing Scientific Group. His research interests include the ecology and biogeography of plankton species and communities, notably their response to environmental changes. He has participated in 17 marine science voyages to Antarctica.

Alexandra POST is a marine geoscientist, with expertise in benthic habitat mapping, sedimentology and geomorphic characterisation of the seafloor. She has worked at Geoscience Australia since 2002, with a primary focus on understanding seafloor processes and habitats on the East Antarctic margin. Most recently she has led work to understand the biophysical environment beneath the Amery Ice Shelf, and to characterise the habitats on the George V Shelf and slope following the successful CAML voyages in that region.

Yan ROPERT COUDERT spent 10 years at the Japanese National Institute of Polar Research, where he graduated as a Doctor in Polar Sciences in 2001. Since 2007, he is a permanent researcher at the CNRS in France and the director of a polar research programme (since 2011) that examines the ecological response of Adélie penguins to environmental changes. He is also the secretary of the Expert Group on Birds and Marine Mammals and of the Life Science Group of the Scientific Committee on Antarctic Research.