Environmental Setting

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 into 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 delimiting factor 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 (Barnes 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 ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001), while shelf banks have been preserved as relatively shallow areas through the bypass of the mobile ice sheet around these broad basins and shelf edges (e.g. Harris et al. 2001). 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 guide to the broad-scale distribution of benthic communities (Barry et al. 2003, Belay et al. 2010, Post 2011), and benthic...
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.)
Environmental Setting

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 fecal 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 Smethie 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 found at depths of 150–200 m and 600–900 m (Hauck et al. 2012). Fine grained carbonate sediments are also extensive on ridges, plateaus and rises, where these features are 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 morpholgy mean that these features can be used to expand our understanding of the nature of the seabed environment.

### Table 1 Description of geomorphic features mapped in this study.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelf bank</td>
<td>Banks on the shelf at depths &lt;500 m and therefore subject to iceberg scouring.</td>
</tr>
<tr>
<td>Cross shelf valley</td>
<td>Areas on the shelf delineated by closed contours deeper than 500 m.</td>
</tr>
<tr>
<td>Coastal terrace</td>
<td>Shelf depressions, commonly shallower than 500 m, that are connected to the shelf edge by valleys.</td>
</tr>
<tr>
<td>Island coastal terrace</td>
<td>Mapped as for coastal terrace around large, rugged islands.</td>
</tr>
<tr>
<td>Ice shelf cavity</td>
<td>Areas beneath floating ice tongues.</td>
</tr>
<tr>
<td>Upper slope</td>
<td>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).</td>
</tr>
<tr>
<td>Trough mouth fan</td>
<td>Broad aprons of sediment on the upper slope, extending from the shelf break to 2500–3000 m water depth.</td>
</tr>
<tr>
<td>Structural slope</td>
<td>Low relief topographic features formed from underlying structures, such as basement protrusions, that extend beyond the lower slope.</td>
</tr>
<tr>
<td>Margin ridges</td>
<td>Large protrusions extending hundreds of meters above the abyssal plain formed from igneous or basement intrusions.</td>
</tr>
<tr>
<td>Marginal plateau</td>
<td>Areas of relatively flat seafloor that extend from the continental margin, but are separated from the shelf by a saddle.</td>
</tr>
<tr>
<td>Abyssal plain</td>
<td>Smooth, sediment-covered area of seafloor.</td>
</tr>
<tr>
<td>Contourite drift</td>
<td>Mounds of sediment that rise gently above the surrounding sea floor, constructed by strong bottom currents.</td>
</tr>
<tr>
<td>Rough seafloor</td>
<td>Rugged seafloor consisting of a mixture of hard and soft substrates reflecting the protrusion of small basement hills and ridges beneath the sediment surface.</td>
</tr>
<tr>
<td>Seamount</td>
<td>Roughly circular areas which rise above the surrounding sea floor by at least 1000 m.</td>
</tr>
<tr>
<td>Seamount ridges</td>
<td>Elevate ridges which are hundreds to thousands of meters above the surrounding seafloor.</td>
</tr>
<tr>
<td>Mid ocean ridge valley</td>
<td>Elevate troughs several hundreds of meters deeper than the seafloor, with a pronounced central rift valley.</td>
</tr>
<tr>
<td>Fracture zone</td>
<td>Sleepy cliffs developed on major crustal fracture zones, formed during rifting and seafloor spreading.</td>
</tr>
<tr>
<td>Trough</td>
<td>Closed elongate depressions more than 4500 m deep and hundreds of kilometers long. Mostly straight.</td>
</tr>
<tr>
<td>Trench</td>
<td>Arcuate areas of very deep ocean floor, more than 5000 m deep. Formed by subduction of oceanic crust at convergent plate margins.</td>
</tr>
<tr>
<td>Island arc</td>
<td>Arcuate ridges capped with volcanic islands formed adjacent to subduction zones.</td>
</tr>
<tr>
<td>Volcano</td>
<td>Active volcanoes that impinge directly on the marine environment.</td>
</tr>
<tr>
<td>Plateau</td>
<td>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.</td>
</tr>
<tr>
<td>Plateau slope</td>
<td>Broad sloping regions around the margins of large plateaus.</td>
</tr>
<tr>
<td>Ridge</td>
<td>Elevate ridges that extend from large plateaus and other features.</td>
</tr>
<tr>
<td>Wave affected bank</td>
<td>Areas of banks shallower than 200 m which are likely impacted by large, long period swells and storm waves.</td>
</tr>
</tbody>
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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 fecal 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 Smethie 1985, Nelson et al. 1995, Hauck et al. 2012).

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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 grain-size 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, Koublibbi et al. 2010, Post et al. 2011), the NW Atlantic (Thouveneau et al. 1991, Kostylev et al. 2001), the Great Barrier Reef (Beanam & 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, Thølking 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. Zinnemann & Feldman 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 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) 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 (Davies et al. 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 ice, 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. 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 km² in February to 18 million km² in September (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 (Massom et al. 2010). 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 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). The response of fast ice is not well understood, though a projected increase in iceberg numbers may lead to greater fast ice extent in some regions.

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 3, 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

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.
important early-season food source for pelagic herbivores during late winter and early spring, when food in the water-column is scarce.

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 Eusaurus antarcticus and E. tridentatus (Krapf 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 foraminifera, turbellarians, nematodes, gastropods, and cephalopods (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. 2010). 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 (Nicot 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 hypothesized 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 (Nicot 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 Gondogene sia antarctica (cited as Pontogene sia 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 mourning 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). Polynya 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 invertebrates, which are typically more abundant than in open waters (Brierley et al. 2002). From the ice edge, diving predators can access under-ice communities of fish and invertebrates, which are typically more abundant than in open waters (Brierley et al. 2002). From the ice edge, diving predators can access under-ice communities of fish and invertebrates, which are typically more abundant than in open waters (Brierley et al. 2002). From the ice edge, diving predators can access under-ice communities of fish and invertebrates, which are typically more abundant than in open waters (Brierley et al. 2002). From the ice edge, diving predators can access under-ice communities of fish and invertebrates, which are typically more abundant than in open waters (Brierley et al. 2002).
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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 by exporting the Antarctic heat content to the north and by transporting carbon, nutrients, and other materials around the globe.

The ACC is divided into two components: the Antarctic Circumpolar Current (ACC) and the East Wind Drift (EWD). The ACC is characterized by strong southward-flowing currents that separate the warmer subtropical anticyclonic gyres (circular wind-driven ocean currents) that exist in the Pacific, Atlantic, and Indian Ocean basins. The ACC has a subpolar 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, CO2, nutrients, and other tracers around the globe.

The ACC itself is made up of a number of 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 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, merging and splitting again over time (Sokolov & Rintoul 2009).

The ACC and the ACC itself are 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 conveyed eastwards 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 subtropical 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 north loses buoyancy through atmospheric cooling and 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) that sinks and spreads northwards to fill the deepest parts 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 (Cunningham et al. 2003). South of the SAF is the Subantarctic Front (SAF). This may be further split into Upper CDW (UCDW) and Lower CDW (LCDW). UCDW is characterised by an oxygen minimum and nutrient maxima, while LCDW has a salinity maxima and both have high levels of dissolved inorganic carbon. South of the SAF is the Polar Front (PF) which is dominated by the abyssal cold waters below the CDW. Its Antarctic shelf origin means that it has high oxygen, low temperature and low salinity similar 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 and temperature 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 (less than 300 m with temperatures below 1.8°C). 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 upper layer of the AZ is the remnants of the winter time base of the mixed layer (Whitworth & Nowels 1987) and shoals towards the pole. The lower 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 fertilize 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).

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

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).
2.8. Sub-polar water masses

Whithworth et al. (1998) provide a comprehensive assessment of circumpolar water mass characteristics and distributions for the sub-polar region of the Southern Ocean. As the surface layer of the Antarctic Intermediate Water (AAIW) is exchanged across the sub-polar front, and as it is locally forced by the winds it is also not as sharply defined as the ACC fronts. 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).

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 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. The surface layer of the SW is exchanged across the ASC, and as it is locally forced by the winds it is not as sharply defined as the ACC fronts. 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).

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Newly formed SW accumulates in the depressions rather than being exported and mixed away by the ACC. 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 impacted by 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 circulating 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 deep waters, acting to renew the ocean interior (Marsh & 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 pump the vertical layers up or down, the lateral flux of heat and freshwater through current advection or eddy stirring, and the background density (pycnocline). The depth of the mixed layer is influenced by horizontal density gradients that develop over time or in response to wind or fresh input (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 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 $T_{min}$ 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 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).
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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. While 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).

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 diverges 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.

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.

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:

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 gyres 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 high 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.

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 topographic features with the ACC drives upwelling. The locations of the upwelling maxima, and thus the implied areas of high surface nutrients, are associated with 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.
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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).

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...
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).
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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 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 ($\sigma_\theta$) are overlain to show gyre structure.
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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