Antarctic sea ice change and variability − Physical and ecological implications

Robert A. Massom[a,b,*], Sharon E. Stammerjohn[c]

[a] *Australian Antarctic Division, Dept. of the Environment, Water, Heritage and the Arts, Channel Highway, Kingston, Tasmania 7050, Australia*
[b] *Antarctic Climate and Ecosystems Cooperative Research Centre, Private Bag 80, c/o University of Tasmania, Hobart, Tasmania 7001, Australia*
[c] *Ocean Sciences Department, University of California, Santa Cruz, CA 95064, USA*

Abstract

Although Antarctic sea ice is undergoing a slight increase in overall extent, major regional changes are occurring in its spatio-temporal characteristics (most notably in sea ice seasonality). Biologically significant aspects of Antarctic sea ice are evaluated, emphasising the importance of scale and thermodynamics versus dynamics. Changing sea ice coverage is having major direct and indirect though regionally-dependent effects on ecosystem structure and function, with the most dramatic known effects to date occurring in the West Antarctic Peninsula region. There is mounting evidence that loss of sea ice has affected multiple levels of the marine food web in a complex fashion and has triggered cascading effects. Impacts on primary production, Antarctic krill, fish, marine mammals and birds are assessed, and are both negative and positive. The review includes recent analysis of change/variability in polynyas and fast ice, and also highlights the significance of extreme events (which have paradoxical impacts). Possible future scenarios are investigated in the light of the predicted decline in sea ice by 2100 e.g. increased storminess/waviness, numbers of icebergs and snowfall. Our current lack of knowledge on many aspects of sea ice-related change and biological response is emphasised.
© 2010 Elsevier B.V. and NIPR. All rights reserved.

Keywords: Antarctic sea ice; Climate change; Ecological impacts; Icebergs; Ice sheet; Ocean

1. Introduction − The importance of Antarctic sea ice

Antarctic sea ice is a highly dynamic material that extends over a vast area of the circumpolar Southern Ocean that ranges from ∼19 million km^2 each September to ∼3−4 million km^2 each February (Comiso and Nishio, 2008; Gloersen et al., 1992). In so doing, it plays a crucial and highly dynamic and variable role in the global climate system and the life cycles of high-latitude marine organisms. By forming an insulative, high albedo "skin" (albeit thin and discontinuous) on the ocean surface, sea ice and its snow cover seasonally modulate exchanges of heat, gases and momentum between the high-latitude ocean and atmosphere and also the radiative and thermodynamic properties of the surface. Moreover, seasonal brine rejection from sea ice formation and freshwater

---

* Corresponding author. Australian Antarctic Division, Dept. of the Environment, Water, Heritage and the Arts, Channel Highway, Kingston, Tasmania 7050, Australia. Tel.: +61 3 6226 7647; fax: +61 3 6226 7650.

E-mail address: r.massom@utas.edu.au (R.A. Massom).

pulses from ice melt are key determinants of the upper ocean freshwater budget, and in certain key Antarctic coastal locations the formation of cold, dense oxygen-rich Antarctic Bottom Water (AABW) is a crucial driver of the global ocean circulation (the thermohaline "conveyor belt") (see Lubin and Massom (2006) and references therein). The magnitude of these impacts depends not only on the areal extent of the ice but also on its concentration, dynamics, ice-type and thickness distribution, degree of deformation and snow cover characteristics – and their complex inter-relationships and spatio-temporal characteristics. Seasonality is a crucial factor, with the annual expansion and contraction of sea ice representing one of the largest annual physical and albedo variations on Earth.

Sea ice further plays a pivotal role in the biogeo-chemical cycles of the Southern Ocean (Thomas et al., 2009), is a dominant seasonal force in the structure and dynamics of high-latitude marine ecosystems, and significantly affects all trophic levels that are specifi-cally adapted and attuned to its presence, seasonal rhythms and properties (Arrigo et al., 2009; Bluhm et al., 2009; Brierley and Thomas, 2002; Caron and Gast, 2009; Deming, 2009; Dieckmann and Hellmer, 2009; Eicken, 1992; Moline et al., 2008; Tynan et al., 2009). Sea ice significantly contributes to vari-ability in high-latitude primary production by serving as a substrate for concentrated algal biomass and growth; affecting nutrient dynamics, ocean stratifica-tion and light availability; and generating extensive phytoplankton blooms upon its melt in spring–summer (Arrigo et al., 2008; Smith and Comiso, 2008). The standing stock of algae contained within the sea ice cover provides a crucial food source for grazers such as Antarctic krill (*Euphausia superba*) during times of the year when food resources in the water column are low (Quetin and Ross, 2009). In fact, Antarctic krill are highly dependent on sea ice at various critical stages of their life cycle (Quetin and Ross, 2009; Smetacek et al., 1990). Sea ice also serves as a key habitat, refuge and barrier to air-breathing predators (Tynan et al., 2009).

Sea ice also plays a key though poorly understood role in regulating the Southern Ocean "biological pump" and the uptake and sequestration of atmo-spheric CO_2 (Tréguer and Pondaven, 2002), as well as ocean upwelling and outgassing and ocean acidifica-tion (Fabry et al., 2009). Emerging work suggests that sea ice is not simply an impermeable barrier to exchanges of climatically-important gases between the ocean and atmosphere, but plays an important seasonally-dependent role as both a source and sink

and in biogeochemical cycling (Delille et al., 2007; Dieckmann et al., 2008). Climate-change feedbacks such as ocean warming, reduced sea ice coverage/increased sea ice melt and changing patterns of deep-water ventilation potentially alter future surface ocean carbonate conditions and acidification of the Southern Ocean (McNeil and Matear, 2008). Ocean acidification in turn represents a major threat to calcified marine organisms (Moy et al., 2009). The exact nature of the role played by sea ice in ocean acidification is not well understood, but is likely to be complex (Fabry et al., 2009).

Given the factors outlined above, a major concern is that any changes in the coupling between sea ice, ocean circulation and biogeochemical cycles could result in positive feedbacks that drive further climate change (e.g. Turner et al., 2009a). Significant change in Antarctic sea ice (positive or negative) has major climatic and ecological ramifications – the former extending well beyond the ice-covered domain. Sea ice forms, evolves and melts in response to synoptic- to seasonal-scale patterns in atmospheric and oceanic forcing and is highly sensitive to changes in these patterns. Sea ice is not only a sensitive indicator of climate change (and variability), but is also a key agent of change through feedback mechanisms involving the coupled atmosphere–ice–ocean system, most notably the ice-albedo feedback (Allison et al., 2001; Goodison et al., 1999; Ledley, 1991; Simmonds and Jacka, 1995). Moreover, sea ice in the coastal zone interacts strongly with aspects of the ice sheet (modulating heat and moisture fluxes and lateral/basal melt rates), and changes in the latter will impact the sea ice zone (Massom et al., 2001a).

While much attention is focussed on the major changes occurring in Arctic sea ice coverage (e.g. Stroeve et al., 2007), major rapid changes are also taking place in regions of Antarctica (e.g. Stammerjohn et al., 2008a; Vaughan et al., 2003). In the west Antarctic Peninsula (WAP) region as in the Arctic, these changes have been particularly rapid, with strong responses being observed in the marine ecosystem (Moline et al., 2008). In this paper, we evaluate recent Antarctic sea ice change and variability (effectively over the satellite passive microwave era since the late 1970s), present examples of observed biological/ecological impacts, and discuss possible future scenarios. We preface this with a brief descrip-tion of fundamental physical factors and processes that shape Antarctic sea ice as a biological, ecological and biogeochemical agent (more detailed information on Antarctic sea ice as a habitat and its modelling and

measurement is given in Massom et al., in preparation). Emphasis will be on the importance of understanding the response of various measures of sea ice (e.g. concentration, duration, extent, thickness) in order to better understand the impact of climate-related changes on high-latitude ecosystems. For example, one of the key driving forces of ecosystem response to seasonal sea ice is the timing of autumn ice edge advance and spring retreat (Stammerjohn et al., 2008b), variability that is obscured by any kind of space-time averaging (e.g. regional monthly averages of sea ice extent).

2. Biologically important attributes of Antarctic sea ice

2.1. The sea ice environment

The circumpolar Antarctic pack ice zone is highly dynamic. Its basic building blocks are assemblages of floes of differing size that constantly drift at typical rates of ∼15–20 km per day (Heil and Allison, 1999). Moreover, large synoptic-scale variability is superimposed on the seasonal waxing and waning of the ice cover. The seasonal sea ice zone (SSIZ) represents one of the largest, most dynamic and most productive marine ecosystems on Earth (Brierley and Thomas, 2002; Clarke et al., 2008). Driven by the annual advance-retreat cycle, the sea ice comes into contact and interacts with several important physical and biological boundaries and zones (Nicol et al., 2008). These include the eastward-flowing Antarctic Circumpolar Current (Tynan, 1998), the Antarctic Divergence (an important zone of upwelling), the continental shelf break, and the westward-flowing near-coastal East Wind Drift or Antarctic Coastal Current. Another important, and more stable, sea ice element is the relatively narrow coastal landfast ice zone (see Section 2.2) which, unlike pack ice, is relatively stationary.

Considerable emphasis is typically placed on sea ice extent when discussing hemispheric sea ice change and variability and its relation to biological and biogeochemical variability. However, while extent is undoubtedly important as a descriptor of sea ice areal coverage and its influence, it is only part of the equation. Changes in sea ice seasonality, in terms of annual day of advance and retreat and resultant ice season duration for a given location appear to more directly explain the alteration of key phenological relationships (Stammerjohn et al., 2008b). A major concern, borne out by recent integrated observations from the Palmer

Long-Term Ecological Research (LTER) project, is that changes in the timing of sea ice advance and retreat lead to changes in habitat, food type and availability, species distributions and thus ecosystem dynamics and biogeochemical cycling (Ducklow et al., 2007).

Other crucial factors or "building blocks" embedded within the sea ice spatio-temporal domain include concentration, ice and snow cover properties and thickness, floe-size, ice-type distribution (particularly thin versus thick ice), drift and degree of deformation, and meteorological history. Moreover, the circumpolar ice edge seldom forms a sharp and clear-cut boundary between ice and ocean (although such ice edges can form under persistent northerly wind conditions, e.g. Massom et al., 2006, 2008). Rather, it generally constitutes a diffuse zone up to 10s of kilometres wide (Fig. 1a). The characteristics of the outer zone of the pack, termed the "marginal ice zone" (MIZ), are strongly determined by ocean wave–ice interaction processes (Squire, 2007; Wadhams, 2000). In the outer few tens to hundreds of kilometres of the pack and adjacent to polynyas and large leads, wave–ice interaction plays a fundamental role in i) sea ice formation (Fig. 1b), evolution, thickness distribution, concentration, floe-size distribution (Fig. 1c and d) (Fox and Haskell, 2001) and mechanical breakup and melt (Wadhams, 2000); and ii) in sculpting snow cover distribution and properties (Massom et al., 2001b). It also contributes to the breakup of fast ice (Langhorne et al., 2001), particularly during spring–summer in the absence of a surrounding protective pack-ice cover. Its influence is felt not only in the MIZ but also across large areas of the pack on occasions, due to the propagation of long-period waves through the pack e.g. Squire et al. (1986), Massom et al. (1999). Moreover, wave–ice interaction represents a key ecological process over a large area of the circumpolar sea ice zone by removing snow and introducing water, nutrients and biological material onto the sea ice surface (Fig. 1c), leading to the formation of surface pond communities. In spite of their overall significance, however, ocean surface waves are typically neglected in coupled sea ice models and GCMs, which treat the sea ice cover as a continuum.

Snow cover on sea ice plays an important role in the following (see Sturm and Massom, 2009 and references therein):

- The thermodynamics, growth rate and microstructure of the underlying ice (as an efficient insulator),
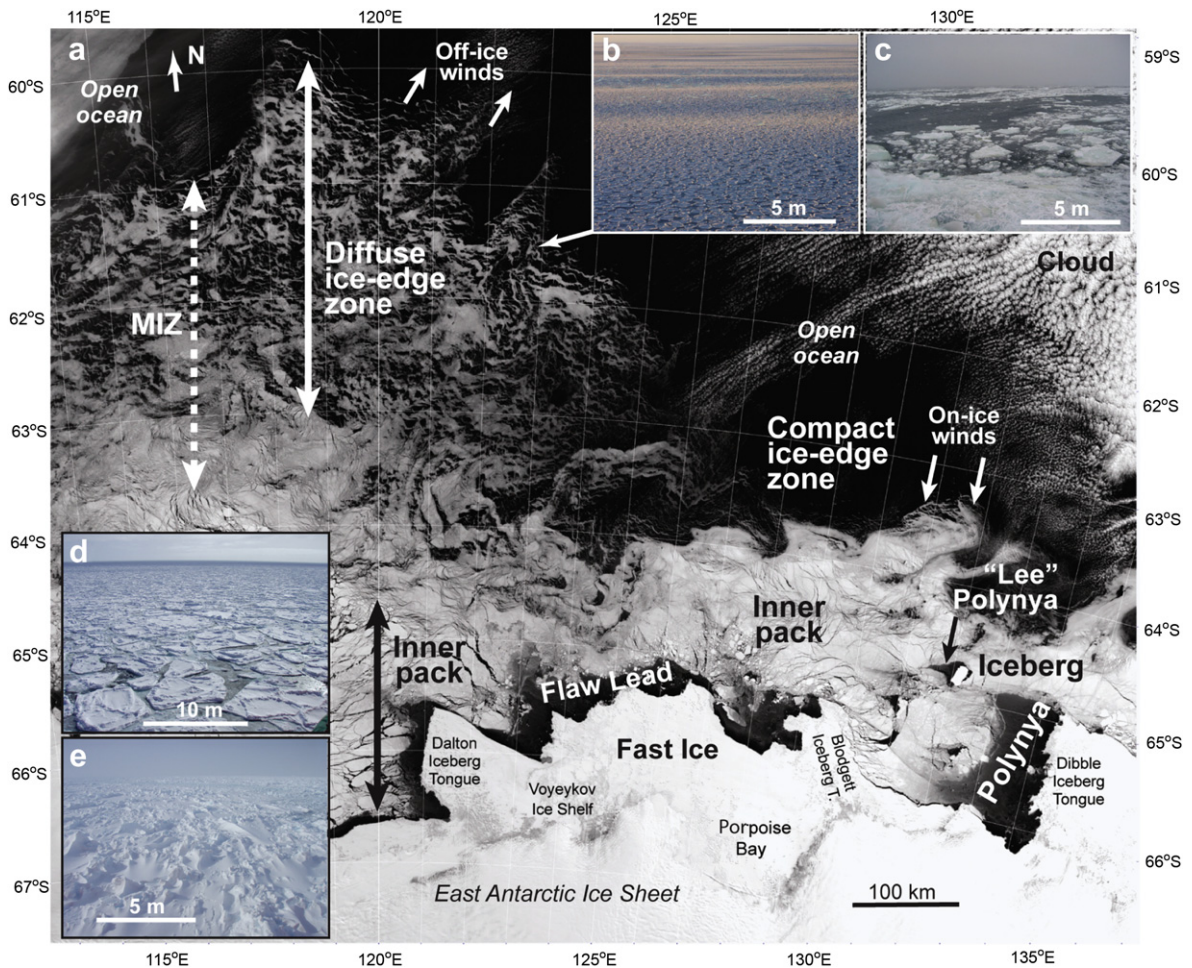
Fig. 1. a) NASA Terra MODIS satellite visible image (resolution 250 m) of the East Antarctic sea ice zone from ∼112 to 137°E, showing that the sea ice edge zone can be either diffuse (comprising series of bands) or compact depending on wind direction (image courtesy NASA). Photographs taken from a ship and illustrating the widely different sea ice conditions present within the SSIZ in winter: b) pancake ice formation in the marginal ice zone (MIZ) with ocean swell; c) brash ice and floe fragments close to the outer margin of the ice edge zone; d) thin first-year (FY) ice deeper in the pack with a thin snow cover, with small floes fragmented by wave–ice interaction; and e) heavily-deformed thick FY ice with a thick snow cover in the inner pack ice zone, showing pressure ridges and rubble fields and snow drift features. Although also affected by storms and internal ice interaction, mean floe size tends to increase with increasing distance from the open ocean or large bodies of open water (Fox and Haskell, 2001).

thereby affecting the temperature, salinity and permeability histories of the ice (Golden et al., 1998);

- The ice optical properties by regulating and greatly reducing the penetration of solar radiation (including harmful UV radiation and beneficial photosynthetically-available radiation [PAR]) into the ice and underlying ocean (Perovich, 2001);
- Maintaining the sea ice cover (by virtue of the important ice/snow-albedo feedback mechanism); and
- Extensive flooding of the sea ice surface by loading and depressing the surface below sea level. Such flooding not only leads to widespread ice formation at the sea ice surface in the form of "snow-ice"

(Maksym and Markus, 2008) but also again brings nutrients and organisms up to the surface and affects algal dynamics in the ice (Fritsen et al., 1998).

Biological implications of changes in snowfall and windiness are examined in Section 7.

Ice thermodynamic and meteorological histories are also key factors. Changeable vertical temperature gradients through the snow and ice column drive rapid snow metamorphism (Sturm and Massom, 2009) and alter the microstructural properties of the ice (including its permeability, which also depends on salinity (Golden et al., 1998)). Air temperatures fluctuate rapidly on

synoptic scales as storms traverse the pack ice, with extensive ephemeral melt episodes occurring even in winter when northerly winds predominate (Massom et al., 1997). Under exceptional circumstances, northerly winds can persist for weeks to months (Massom et al., 2006). Such episodes that may be becoming more frequent in certain regions (see Section 5).

As a result of the ability of sea ice to incorporate particulate matter, its algal biomass is considerably greater than in the underlying upper water column (Quetin and Ross, 2009) during autumn through early spring. Initially, the amount of biological material incorporated in the sea ice matrix depends on its mode of formation i.e. frazil ice formed under turbulent conditions can entrain a higher concentration of biological material than columnar-type ice formed under more quiescent conditions. This occurs by virtue of the ability of frazil ice crystals to "scavenge" particulate matter as they rise through the upper water column (Garrison et al., 1983). The sea ice and snow cover also accumulate iron, which is an essential micro-nutrient for phytoplankton growth and is thus intimately involved in marine primary productivity and carbon export (Lannuzel et al., 2007). Although the ice edge zone is the site of enhanced biological activity throughout the year, the release of ice algae and nutrients into the upper ocean each spring combines with higher light levels and a stabilizing pulse of meltwater to activate extensive algal blooms (Arrigo et al., 2008; Smith and Comiso, 2008). These are in turn of immense importance to higher trophic levels. For example, elevated concentrations of Antarctic krill have been observed just poleward of the ice edge in the SW Atlantic (Brierley et al., 2002). Causes of yearly variability in the location, spatial extent and intensity of phytoplankton blooms vary and include variability in sea ice spatio-temporal characteristics, winds, cloud cover, sea-surface temperature, nutrients and grazing (e.g. Arrigo et al., 2008). The complexities of the impact of the seasonal sea ice cycle on annual primary production and the timing and magnitude of blooms were assessed by Vernet et al. (2008).

2.2. The importance of scale

Determining how sea ice change (trends and fluctuations) affects Antarctic oceanic ecosystems requires knowledge of how physical and biological processes interact over a range of spatial and temporal scales, these processes being key determinants of high-latitude marine ecosystem structure and function (Murphy et al., 1988, 2007). This represents a considerable

challenge given the broad range of scales involved; these are represented schematically with a simplified part of the Antarctic marine food web in Fig. 2. Moreover, the system is far from static but rather is constantly evolving, and analyses of temporal variability are essential to provide insight into responses to natural variability e.g. due to El Niño-Southern Oscillation or ENSO (Turner, 2004)

On spatial scales of microns to millimetres (the realm of viruses, bacteria and algae etc.), sea ice is a composite of pure ice, brine, air and salt inclusions that exhibits substantial heterogeneity, with its microstructure being determined by the processes of ice formation or melt; the subsequent temperature and salinity history of the ice profile; the interaction of physical, chemical and biological processes; and the distribution of vertical brine drainage channels (Petrich and Eicken, 2009; Weeks and Ackley, 1986). At the centimetre-to-metre scale, micro-organisms proliferate in a variety of sea ice habitats which are conventionally designated by their location within the vertical sea ice column e.g. surface, interior and bottom (Horner *et al.*, 1992; Arrigo et al., 2009). Micro-organism distributions within sea ice tend, however, to be horizontally heterogeneous on scales of metres to tens of metres (Arrigo et al., 2009), as do sea ice and snow cover thickness and properties (Lubin and Massom, 2006; Sturm and Massom, 2009), with small-scale variations in ice morphology being compounded by deformational processes (Haas, 2009).

At intermediate scales, the sea ice zone is permeated by extensive networks of leads, which are generally ephemeral openings formed under divergent sea ice conditions in response to the passage of storms and internal ice stresses. Although relatively narrow, leads can run for 100s of kilometres and constitute areas of locally-enhanced sea ice formation in autumn to early spring, sea ice meltback in late spring–summer, skylights into the upper ocean and "highways/arterial routes" which, along with polynyas, enable birds and mammals to survive deep within the sea ice zone (even in winter). The passage of storms also leads to periods of convergence in the sea ice motion field to cause rapid dynamic thickening of the existing ice by rafting and pressure ridge formation. This synoptic "reworking" breaks the ice up into assemblages of different floe sizes, ice-types/ages and snow cover thicknesses, and has a major impact on the incorporation of biological material into, and its subsequent properties and characteristics within, the sea ice column. Moreover, it creates an over-rafted habitat of metre-scale gaps and "caves" within the pack ice that appears to be an
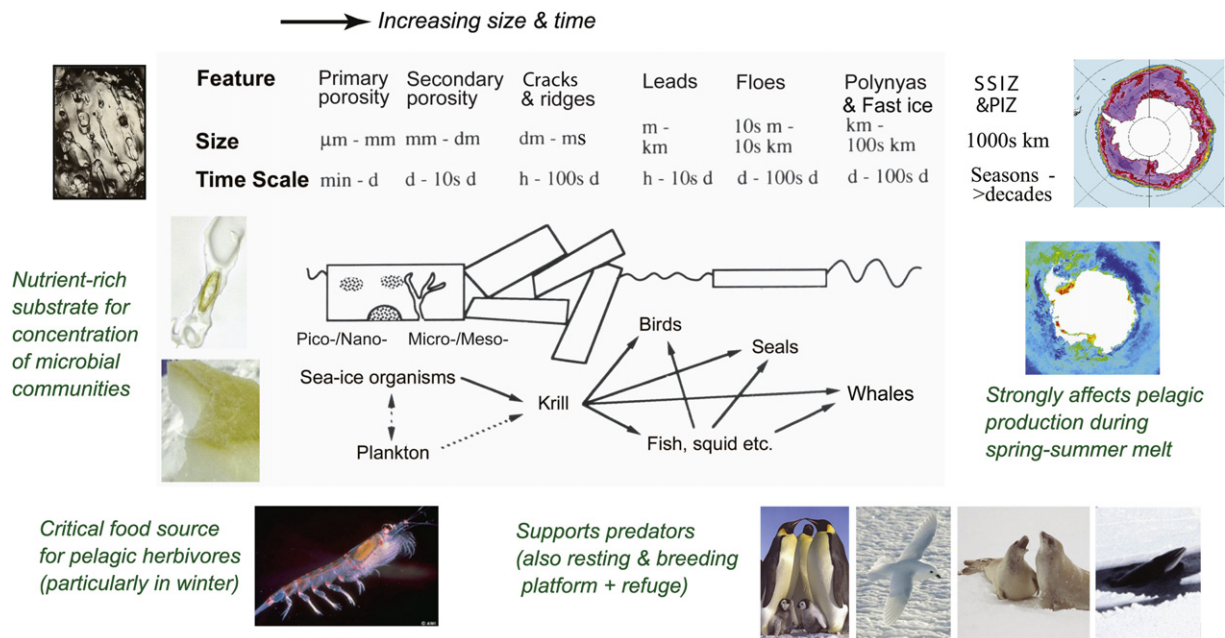
Fig. 2. A schematic of dominant spatial and temporal scales, increasing from left to right (where dm is decimetre), of sea-ice characteristics matched with a simplified part of the Antarctic marine food web (the latter based on Murphy et al., 1988). Time scale in this case refers to the approximate temporal framework within which features change in appearance, where *h* is hour, *d* is day, and *s* signifies multiples. PIZ is perennial ice zone. Working anticlockwise from top left, the insets are: i) a photo-micrograph of sea ice showing brine drainage channels and brine/air inclusions (courtesy Ken Golden); ii) a close-up of a brine drainage channel containing ice algae, and the base of over-turned first-year ice covered in algae (courtesy Jan Lieser and Christopher Krembs); iii) an Antarctic krill (courtesy AWI); iv) photographs of emperor penguins (*Aptenodytes forsteri*), snow petrel (*Pagodroma nivea*) and crabeater seals (*Lobodon carcinophagus*) (courtesy of AAD) and a minke whale (*Balaenoptera bonaerensis*) spy-hopping in a lead; v) composite SeaWiFS ocean colour image of the Southern Ocean showing the distribution of high chl-*a* concentration in spring–summer (courtesy NASA); and vi) monthly composite sea ice concentration image showing maximum annual ice extent (Special Sensor Microwave/Imager [SSM/I] data courtesy NSIDC). Adapted from Eicken (1992).

important habitat for krill and for the over-winter survival of larval krill (Frazer et al., 1997; Marschall, 1988). Other facets of the direct effects of seasonal pack ice "dynamics" on krill population dynamics are reviewed by Quetin and Ross (2009). They stressed that the timing of sea ice retreat influences the timing of food availability for adult female Antarctic krill and thus ovarian development in spring, whereas the timing of sea ice advance is linked to juvenile survival and recruitment success (in the Palmer LTER region). Similarly, Ross et al. (2008) noted a positive correlation in the WAP region between the presence of ice krill (*Euphausia crystallorophias*) and the day of sea ice retreat. In general, ice krill play an important role in structuring food webs in wide continental shelf ecosystems such as the Ross Sea (Smith et al., 2007), whereas Antarctic krill are a key factor in the pelagic environment (Smetacek and Nicol, 2005).

In the coastal zone and at intermediate scales, the sea ice is strongly influenced by interaction with the ice sheet, icebergs and strong and persistent katabatic winds (Massom et al., 2001a). Although coastal polynyas constitute only a small proportion of the overall areal extent of the sea ice zone (estimated at ~1.5% of the mean extent for June–September 1979–2006 by Kern, 2009), they play globally-important roles as:

- Regions of high sea ice production and (in certain cases) associated Antarctic Bottom Water (AABW) formation (Bindoff et al., 2000; Rintoul, 1998);
- Ventilation "windows" between the deep ocean and atmosphere; and
- Sites of early and enhanced meltback of the pack ice in spring–summer (Massom et al., 1999).

Coastal polynyas are also relative "oases" for organisms at all trophic levels throughout the ice season and are sites of major phytoplankton blooms in spring (Arrigo and van Dijken, 2003; Tremblay and Smith, 2007). The location of Emperor penguin (*Aptenodytes forsteri*) colonies is also typically near re-

occurring polynyas (Massom et al., 1998). In some areas (e.g. WAP), these are associated with bathymetric features conducive to upwelling, further enhancing high productivity (Ribic et al., 2008).

Another important component of the coastal zone is fast ice. This forms over a narrow zone (a few kilometres to about 200 km wide) around the ice sheet periphery (Fig. 3), where it constitutes a relatively stationary substrate in sheltered bays, adjacent to promontories and often associated with icebergs grounded in waters <350–400 m deep (Giles et al., 2008a; Massom et al., 2001a). The icebergs act as "anchor points" for fast ice formation (Fig. 3b). An important characteristic of fast ice is its recurrence and persistence in certain locations (where it can form either an annual or perennial cover), and that it is typically separated from the moving pack ice zone by recurrent flaw leads (themselves an important habitat (Fig. 3)). Patterns of fast ice formation and breakup are highly sensitive to changes in atmospheric and oceanic forcing (Heil, 2006; Langhorne et al., 2001; Massom et al., 2009); as such, fast ice is an important indicator of climate change and variability (Murphy et al., 1995).

Although the system exhibits significant heterogeneity on small to local scales, large regional and seasonal-scale patterns recur in sea ice distribution, dynamics and characteristics (Massom et al., in preparation). These take the form of:

- Recurrent zonation within sectors (particularly the East Antarctic);
- Large gyre systems (in the Weddell and Ross Seas and Prydz Bay);
- Regions of recurrent/persistent fast ice formation and perennial pack ice (an area of $3-4 \times 10^6$ km^2 in the western Weddell Sea, Amundsen Sea, Ross Sea and southwestern Pacific Ocean); and
- Coastal or (more rarely) open-ocean polynyas and flaw leads.

At the largest scale is the five-fold change in sea ice areal coverage between winter and summer that forms the seasonal sea ice zone (Comiso, 2003; Gloersen et al., 1992). These large-scale patterns reflect climatological forcing of air temperature, ocean currents, and winds. Once again, a major concern is that regional patterns of Antarctic sea ice seasonality are indeed changing in response to shifts/changes in the forcing fields (Stammerjohn et al., 2008a).

2.3. Thermodynamics versus dynamics

When considering sea ice change/variability, it is important to understand the processes governing its formation, evolution and melt. Sea ice evolution and distribution are governed by the complex interplay of both thermodynamic and dynamic processes (Perovich and Richter-Menge, 2009). The former are shown schematically in Fig. 4. Thermodynamics entails melt/freeze processes and involves the sum of energy fluxes affecting sea ice (Maykut, 1986; Maykut and Untersteiner, 1971). As noted previously, the accumulation of a snow
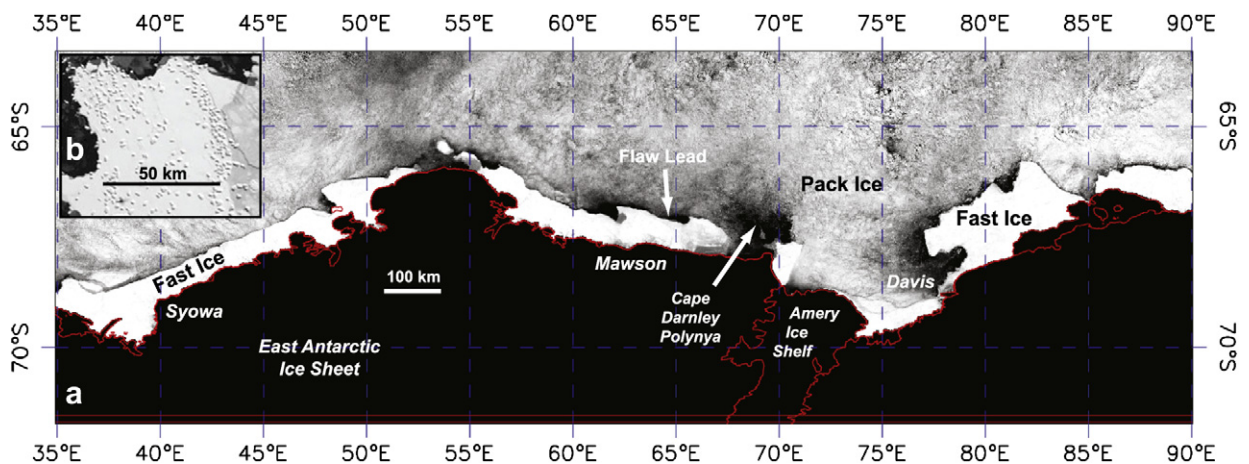

Fig. 3. a) Composite map of fast ice along the East Antarctic coast from 35 to 80°E for the period October 27–November 15, 2008, derived from a compilation of NASA MODIS satellite visible images (spatial resolution 1 km). The compositing was necessary to filter/remove clouds (Fraser et al., 2009). This image is part of a continuous time series along the East Antarctic coast for the period 2000–2008, an aim being to study variability in spatio-temporal characteristics of fast ice distribution (Fraser et al., in preparation). b) Detail from a cloud-free Landsat 7 Enhanced Thematic Mapper image (from the fast ice region to the NE of the Mertz Glacier tongue in Fig. 11) showing the role of small grounded icebergs in anchoring fast ice (courtesy USGS). MODIS fast ice composite courtesy Alex Fraser (IASOS).
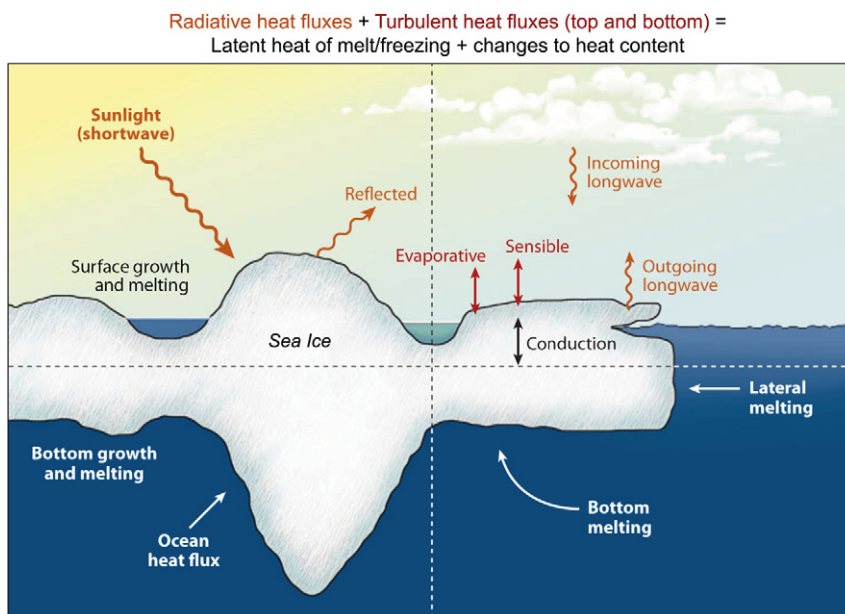
Radiative heat fluxes + Turbulent heat fluxes (top and bottom) =
Latent heat of melt/freezing + changes to heat content

Fig. 4. Schematic of the heat budget of sea ice. Antarctic sea ice freezes at the ice–ocean interface but also at the snow-ice interface through seawater flooding and subsequent freezing producing snow-ice (whereas the melting and refreezing of snow produces superimposed ice, usually in response to winter synoptic variability). The melting of sea ice occurs at the surface, bottom, and lateral edges and can propagate internally. Lateral melt along floe edges and within leads/polynyas is a major determinant of the relatively rapid annual Antarctic meltback, whereas surface melt is a key process in the Arctic, often producing surface melt ponds as shown (the latter are rare in the Antarctic [Andreas and Ackley, 1981]). Also shown above the schematic is the equation for the heat budget of sea ice. Radiative fluxes (orange) include net shortwave and longwave energy (and depend on cloud cover). The turbulent fluxes of sensible and evaporative heat are in red. Changes to heat content (product of temperature, density and specific heat) is ignored at present, although the mechanism that transfers it i.e. conductive energy transfer, is shown in black. Heat loss from the surface of the snow-covered sea ice is balanced by heat supplied to the underside of the ice by the deep ocean, with the difference determining net ice growth or melt. In the Southern Ocean, ocean heat fluxes can be relatively high due to weak ocean stratification (Lytle et al., 2000). Modified from Perovich and Richter-Menge (2009).

cover plays a significant modifying role, given its low thermal conductivity (high insulative capacity) and its high albedo relative to snow-free sea ice (Sturm and Massom, 2009).

Dynamic processes involve the motion and deformation of the ice driven by winds and ocean currents, the dominant factor being wind, with other forces coming into the balance once the ice is in motion i.e. Coriolis effect, internal stress and sea-surface tilt (Hibler, 1986; Leppäranta, 2005). Sea ice motion on daily to weekly time scales responds rapidly to synoptic-scale changes in wind velocity as cyclones pass over or anticyclones prevail. Depending upon whether the ice cover is divergent or convergent, this can result in rapid changes in ice concentration, ice production (and brine rejection) and ice thickness distribution (Haas, 2009).

As stated by Perovich and Richter-Menge (2009), observed changes in sea ice properties and distribution should be interpreted within the context of changing dynamics and thermodynamics, and from the perspective of ice–atmosphere–ocean interactions.

Below, we shall demonstrate that these can be complex and sometimes counterintuitive/paradoxical.

3. Changes in Antarctic sea ice

3.1. The satellite era

We begin with a brief overview of the current "status" of large-scale Antarctic sea ice distribution, based on satellite data analyses. In terms of its overall areal extent and based on the period 1979–2006 (with late-1978 being the start of the multi-frequency satellite passive microwave record), sea ice in the Southern Ocean has exhibited a slight though statistically-significant increase of $0.9 \pm 0.2\%$ per decade (Comiso and Nishio, 2008) (Fig. 5a). This is in stark contrast to the Arctic, where sea ice areal extent is decreasing at an accelerating rate of $3.4 \pm 0.2\%$ per decade (Comiso and Nishio, 2008), with a decreasing rate in summer of 11.3% per decade (Perovich and Richter-Menge, 2009). However, considerable regional contrast and variability are nested within the Antarctic circumpolar
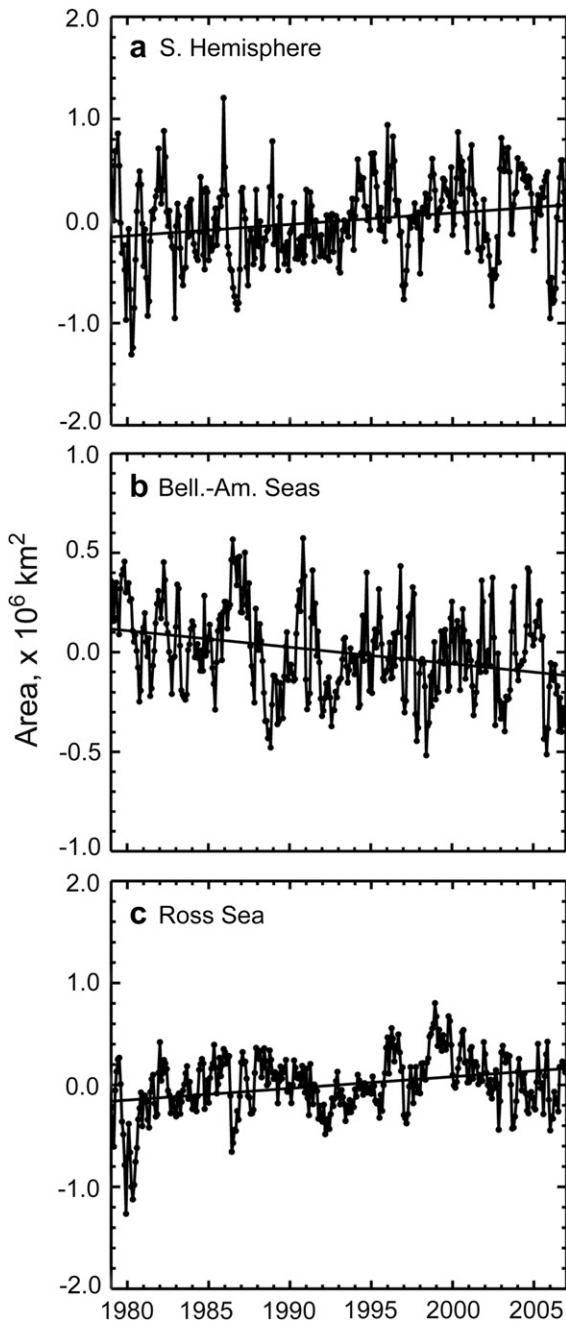
Fig. 5. Satellite-derived monthly anomalies of sea ice extent and trend results in the a) Southern Hemisphere, b) Bellingshausen–Amundsen (Bell–Am) Seas, and c) Ross Sea. The anomalies were obtained by subtracting the monthly climatological averages (i.e. average of all data for a given month for the period November 1978–December 2006) from each monthly average. After Comiso and Nishio (2008).

overview. Most striking are the strongly opposing trends in the adjoining Amundsen–Bellingshausen Seas and Ross Sea sectors (Fig. 5b and c). The former has undergone a statistically-significant decrease of $5.7 \pm 1.0\%$ per decade, whereas a $4.2 \pm 0.7\%$ per decade increase has occurred in the Ross Sea. Reasons for these strong regional contrasts will become apparent through examination of changes in spatio-temporal aspects of the sea ice coverage in more detail. Note that in all cases, complex interannual to decadal variability is superimposed on the 28-year trends.

While significant emphasis is typically placed on overall sea ice extent and its variability and change, this represents only one component of the story. Taking the analysis of the satellite passive microwave dataset a step further and extending earlier work by Parkinson (2002), Stammerjohn et al. (2008a) showed that major and opposing changes have occurred not only in the extent but also in the seasonality of the regional sea ice covers, particularly in the northeast and west Antarctic Peninsula and southern Bellingshausen Sea (AP/sBS, noting here that 'AP' refers to the areas changing to the northeast and west of the Peninsula) and western Ross Sea (wRS) (Fig. 6) – with important physical and ecological consequences. Specifically, annual ice edge advance in the AP/sBS sector is now much later than it was (i.e. a total change of $+54 \pm 9$ days over 1979–2004 within the area enclosed by the 0.01 significance level [black contour] in Fig. 6c), and retreat much earlier (by -31 ± 10 days). This translates to a much shorter duration of the annual sea ice season (by a total of 85 ± 20 days, or a trend of $\sim 3-4$ days/year). The opposite pattern is occurring in the wRS sector (advance 31 ± 6 days earlier and retreat 29 ± 6 days later), resulting in an annual ice duration increase of 60 ± 10 days (or $\sim 2-3$ days/year). In general, advance anomalies are larger and spatially more extensive than retreat anomalies (Stammerjohn et al., 2008a). Patterns elsewhere around Antarctica are of lower magnitude and mixed, but with changes in the timing of advance and retreat that are still of the order of ± 1 day/year. The impacts of these wider changes are less well established.

The primary driving force behind the observed spatio-temporal changes in Antarctic sea ice coverage is thought to be decadal-scale shifts in the dominant modes of atmospheric circulation (large-scale wind patterns) in the Southern Hemisphere (Fogt and Bromwich, 2006), most notably the Southern Annular Mode (SAM or Antarctic Oscillation) (Lefebvre et al., 2004; Liu et al., 2004; Stammerjohn et al., 2008a; Thompson and Solomon, 2002; Yuan, 2004), the
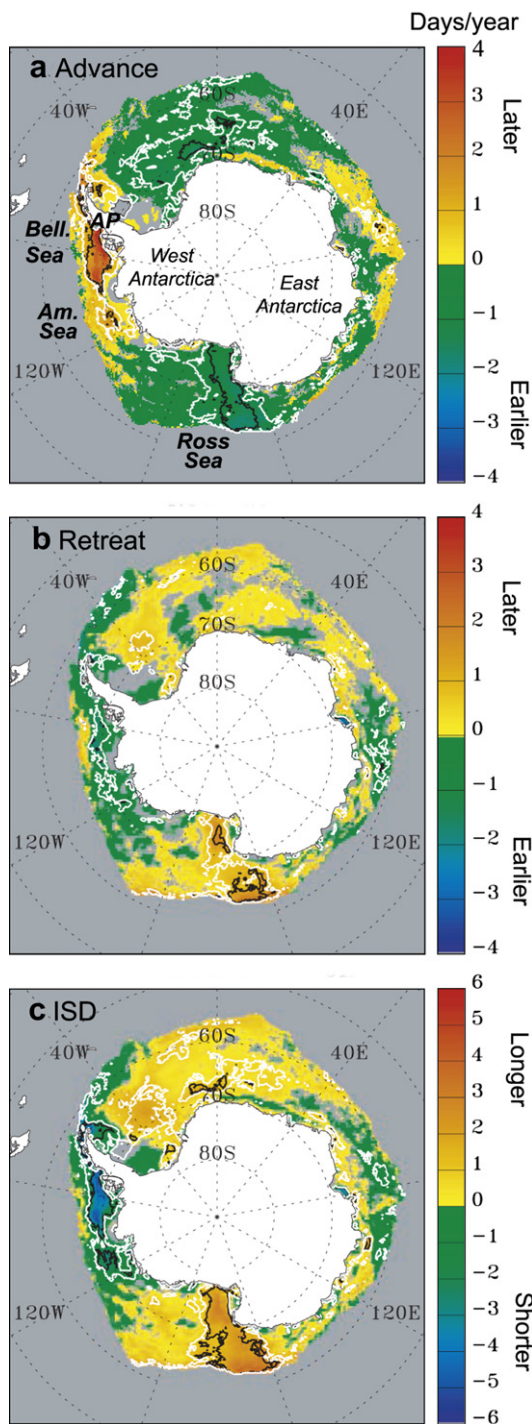
Fig. 6. Trend maps (days/year for 1979–2004) of annual (a) day of advance, (b) day of retreat and (c) ice season duration (ISD). The black/white contours delimit 0.01/0.10 significance levels. Grey shading within the sea ice zone signifies a near-zero trend. AP is Antarctic Peninsula. Modified from Stammerjohn et al. (2008a).

high-latitude response to El Niño-Southern Oscillation (ENSO) (Kwok and Comiso, 2002; Stammerjohn et al., 2008a), and the Wave 3 pattern (Raphael, 2007). The SAM is the dominant mode of atmospheric circulation variability at high southern latitudes and is defined by air pressure differences between mid-latitudes (high pressure) and the Antarctic coast (low pressure) (Thompson and Solomon, 2002). While interactions are complex, major changes in regional sea ice seasonality during roughly the 1980s appear to be related to the predominance of negative SAM, or negative SAM/El Niño, conditions during the austral autumn advance and summer retreat seasons (Stammerjohn et al., 2008a). Under these conditions, the presence of a persistent high pressure anomaly in the high-latitude Southern Pacific (see also Fogt and Bromwich, 2006) led to the predominance of cold southerly winds over the AP/sBS sector (thus favourable conditions for sea ice divergence and persistence), counterbalanced by warm northerly winds (less favourable conditions for extensive and persistent sea ice) in the western Ross Sea (Fig. 7a). In a circumpolar sense, autumn sea ice advance appears to be more sensitive to climate variability than sea ice retreat (Stammerjohn et al., 2008a).

The opposite scenario predominated in the 1990s (and into this current decade), as illustrated in Fig. 7b. During this time, a persistent low-pressure anomaly in the high-latitude South Pacific associated with positive SAM, or positive SAM/La Niña, conditions led to a predominance of warm northerly winds in the AP/sBS sector versus cold southerly winds in the wRS. This explains the later advance/earlier retreat and earlier advance/later retreat in the AP/sBS and wRS sectors, respectively. As such, wind-driven ice dynamics have been a key factor (Harangozo, 2006; Massom et al., 2006, 2008; Stammerjohn et al., 2003), as illustrated in Fig. 8. The change in SAM has been attributed to both increases in atmospheric greenhouse gases (Fyfe et al., 2007; Kushner et al., 2001; Marshall et al., 2004; Shindell and Schmidt, 2004) and the depletion of stratospheric ozone (Thompson and Solomon, 2002; Gillet and Thompson, 2003).

In the WAP region, the sea ice changes have also coincided with an annually-averaged warming in regional surface air temperature records of 2.9 °C over 1951–2005 (http://www.antarctica.uk/met/gjma/temps.html; Stammerjohn et al., 2008a), with the strongest warming occurring in winter (5.8 °C over 1951–2005). The latter is greater than any other warming observed globally (Vaughan et al., 2003). Indeed, the climate of the WAP region is the most
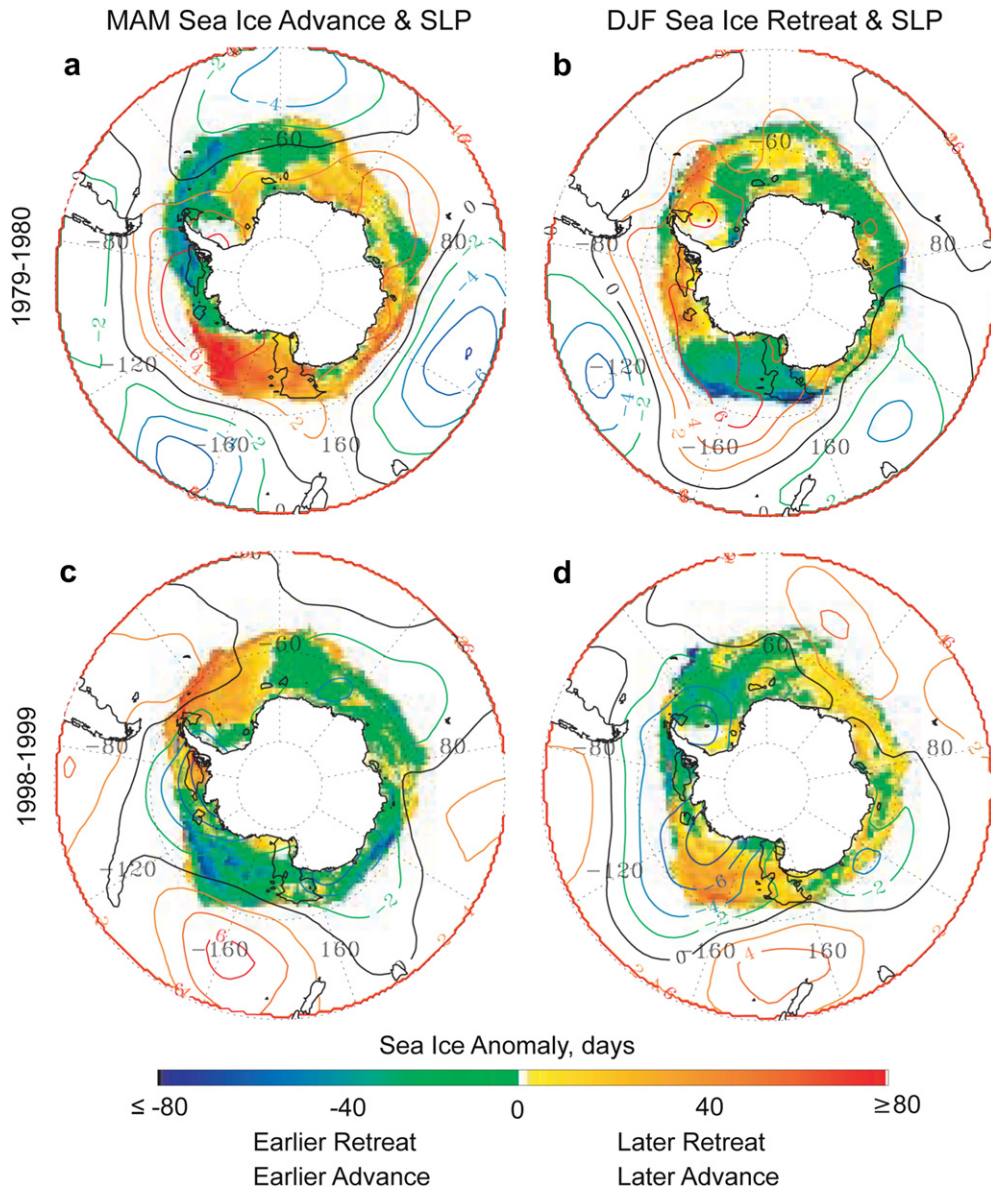
Fig. 7. Southern Ocean annual sea ice advance (March-April-May) and retreat (December–January–February) anomalies for (a, b) 1979–1980 and (c, d) 1998–1999, both versus the 1979–2004 mean. These two years represent the largest ice–atmosphere anomaly years in each decade, and are chosen to illustrate the different regimes. Black contours correspond to regions showing strong trends (at the 0.01 significance level) in sea ice duration (details provided in Fig. 5); coloured contours are sea-level pressure (SLP) anomalies derived from the National Center of Environmental Prediction and National Center for Atmospheric Research Reanalysis (NNR) Project (Kalnay et al., 1996). Modified from Stammerjohn et al. (2008a).

rapidly changing in the Southern Hemisphere (Meredith and King, 2005; Steig et al., 2009). Enhanced snowfall has also been reported as accompanying warmer more northerly winds (Massom et al., 2006, 2008; van den Broeke et al., 2006). Rapid environmental change is also occurring in the terrestrial and glaciological environments in the WAP region e.g. Convey (2007), Scambos et al. (2003).

Other factors that are likely contributing to observed sea ice (and ice shelf) loss in the WAP/sBS sector include increased incursions of warm (1−2 °C) Upper Circumpolar Deep Water onto the continental shelf over the last decade (Klinck et al., 2004; Martinson et al., 2008), with an associated increase in ocean heat content equivalent to a ∼0.7 °C warming of 300 m of the water column beneath the winter mixed
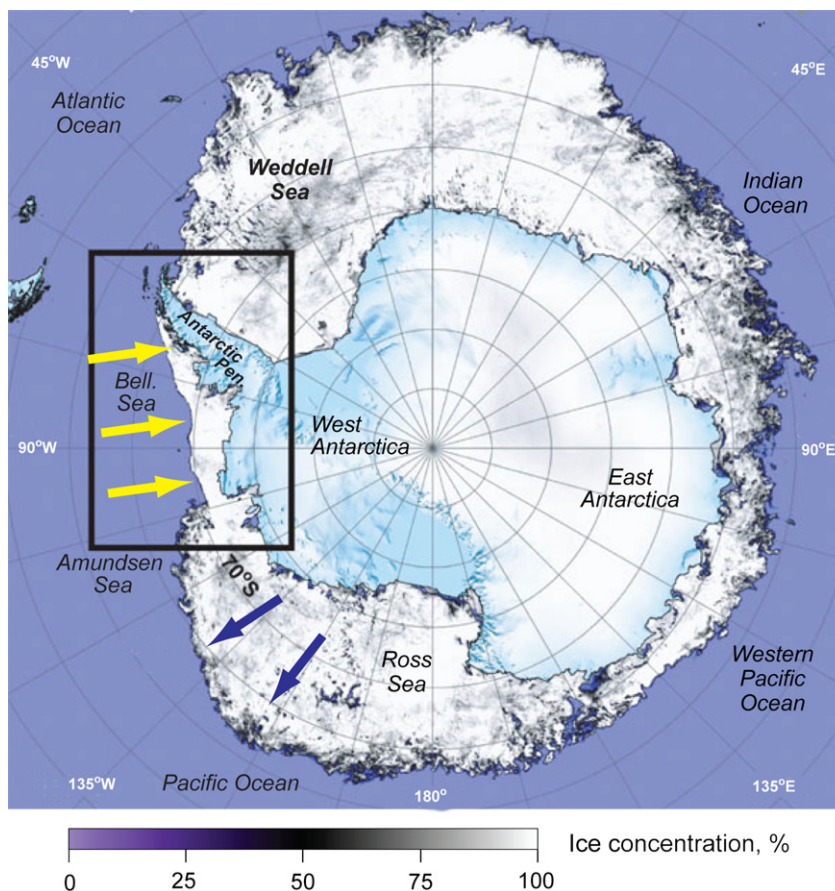
Fig. 8. Map of daily Antarctic sea ice concentration for 3 November 2005 (spatial resolution 6.25 km), derived from NASA Aqua AMSR-E data (obtained from the University of Bremen (www.seaice.de)). Note the extraordinarily well-defined ice edge and compactness of the marginal ice zone in the Bellingshausen and East Amundsen Seas sector from ∼60°W to 105°W compared to the remaining circumpolar pack (where the ice edge zone is largely diffuse). This pattern is indicative of compaction of sea ice against the meridionally-trending barrier of the Antarctic Peninsula driven by a sustained period of strong winds with a dominant northerly component (denoted by the yellow arrows – see Massom et al., 2006, 2008 for details). Conversely, the sea ice zone in the adjacent wRS sector is substantially more diffuse (and extensive). This is indicative of the northward outflow of cold continental air along the western limb of a persistent low-pressure anomaly in the Amundsen Sea (see Fig. 7). Both illustrate the key role of wind-driven ice dynamics in determining pack ice anomalies. Modified from Massom et al. (2008).

layer. A summer warming of sea-surface temperatures by 1 °C and increased upper layer salinification has also occurred (Meredith and King, 2005). The latter changes, thought to be initiated by atmospheric warming, may constitute positive feedbacks that will contribute to continued climate change and sea ice loss (Meredith and King, 2005).

3.2. The pre-satellite era

Unfortunately, the satellite passive microwave record of sea ice concentration and extent that forms the basis of current analyses of change only extends back to late-1978 for multi-frequency data (see Fig. 5), and to 1973 if single frequency data are used.

However, there are a number of sources of proxy information that extend back hundreds of years and, in the case of marine sediment records, many thousands of years. Here, we briefly summarise what is known from the shorter records only (please refer to Armand and Leventer, 2009 for information on palaeo-Antarctic sea ice reconstructions).

Fragmentary information on the past location of the Southern Ocean sea ice edge comes from logbooks of early explorers such as Cook, Ross, Wilkes and Bellingshausen in the late 18th and early 19th centuries. In her compilation of this information, Parkinson (1990) found some suggestion of a more extensive summer-time ice cover compared to 1973–1976 (the early satellite record), but concluded that there was no

conclusive evidence that overall Antarctic ice extent was substantially different in 1770−1850. A difficulty in interpreting earlier ship records relates to the problem of defining a sea ice edge (as discussed earlier), especially from the limited information given. A subsequent comparison of the same historical data with satellite-derived data from 1988−1995 by Wu et al. (1999a) found a reduction in mean ice extent of ∼0.7 degrees of latitude in the latter compared to the earlier epoch. However, an additional factor should possibly be taken into account when comparing earlier ship (or whaling records as discussed below) with satellite observations, namely the apparent underestimate of Antarctic sea ice extent in summer using satellite passive microwave data (Worby and Comiso, 2004).

Using the location of whaling catch records as a proxy for Antarctic summertime sea ice extent, de la Mare (1997) showed an apparent major decline in summertime Antarctic sea ice extent (of 25%) between the late 1950s and early 1970s. This finding was subsequently challenged by Ackley et al. (2003) because of the caveat mentioned above, but also because the whaling records may only reflect regional rather than circumpolar conditions, arguing too that there is some evidence for a larger summertime sea ice extent in the Ross and Weddell Seas in the 1950s. However, additional evidence supporting a major sea ice decline over this immediate pre-satellite period comes from model results e.g. Wu et al. (1999a) and Goosse and Renssen (2005), the fast ice record in the South Orkney Islands (Murphy et al., 1995), and high-resolution analysis of ice sheet core data (see below). Moreover, de la Mare (2008) found in a follow-up study using additional data that Antarctic sea ice changes in the immediate pre-satellite era varied significantly between regions, with most regions showing a decline in sea ice extent while a few showed increases or no significant change. This regional approach is more consistent with current regional differences observed in the satellite data and deserves more closer consideration.

Further, proxy evidence from the Antarctic Ice Sheet points to a sea ice decline since about 1950 (at least in East Antarctica) in broad agreement with the whaling records (de la Mare, 1997, 2008). Ice core analyses are based upon a strong correlation between methanesulphonic acid (MSA) concentrations at Law Dome and 22 years of satellite-derived sea ice extent (Curran et al., 2003). MSA is an oxidation product of dimethylsulphide (DMS) produced by sea ice algae and is thought to occur in higher concentrations in the atmosphere (and therefore glacial ice) during periods of extensive sea ice extent. Curran et al. (2003) used this correlation to apply an instrumental calibration to the longer MSA record (1841−1995 A.D.), producing a proxy record of sea ice extent in the East Antarctic sector 80°−140°E. The results suggest that there has been a 20% decline in sea ice extent since about 1950. The decline is not uniform, however, and shows large cyclical variations with periods of about 11 years (which in turn could weaken trend detection over the relatively short satellite era). Several other studies have reported positive correlations between MSA and sea ice extent (e.g. Foster et al., 2006; Abram et al., 2007; Rhodes et al., 2009), and work is underway to extend this analysis to all available Antarctic sectors. It should be noted that the overall trend in Antarctic sea ice is negative if the 1950−1978 proxy record is added to the satellite data record.

4. Ecosystem responses to sea ice change and variability

In this section, we provide examples of known responses to change and variability in both pack ice and fast ice. These demonstrate that the impacts on ecosystem components are both direct and indirect.

4.1. Pack ice

Much of our current knowledge of the ecological impacts of large regional changes in sea spatio-temporal characteristics comes from the WAP region, due in large part to long-term cross-disciplinary monitoring by coordinated programmes such as the Palmer Long-Term Ecological Research (LTER) project (http://pal.lternet.edu/); the U.S. Antarctic Marine Living Resources (AMLR) programme (http://swfsc.noaa.gov/textblock.aspx?id=551&ParentMenuId=42); the Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) programme (http://www.ccpo.odu.edu/Research/globec_menu.html); and the Rothera Oceanographic and Biological Time Series (RaTS) programme (http://www.antarctica.ac.uk//staff-profiles/webspace/mmm/RaTS/RaTS.html). The response of the marine ecosystem there has been dramatic, rapid and multi-level (Clarke et al., 2007; Ducklow et al., 2007; Moline et al., 2008; Montes-Hugo et al., 2009), and appears to be strongly linked to changing seasonality of sea ice and ocean circulation (e.g. see Deep-Sea Research II 51 (17−19), 55 (3−4), 55(18−19)).

Major changes have been reported in phytoplankton biomass in the WAP region from 1978−1986 to

1998–2006 due to changing wind and sea ice regimes as they affect open water area, ocean mixed-layer depth and light availability (Montes-Hugo et al., 2009). In particular, there has been a statistically significant latitudinal shift towards higher chl-*a* to the south, with latitudinal change in the timing of ice retreat being a key factor (Stammerjohn et al., 2008b). Phytoplankton community composition has also changed (Garibotti et al., 2003), with diatoms diminishing or being replaced by cryptophytes (which are smaller and lack mineral shells) (Moline et al., 2004). This fundamental decrease in phytoplankton size class is likely to recur in the WAP region due to continuing warming, loss of sea ice and increased glacial melt-water input (Moline et al., 2008).

Such major latitudinal shifts at the base of the marine food web have likely contributed to the recently-observed reorganization of northern WAP biota that are directly or indirectly reliant on phytoplankton blooms, notably involving Antarctic krill, Antarctic silverfish (*Pleuragramma antarctica*) and Adélie penguins (*Pygoscelis adeliae*) (Ducklow et al., 2007; McClintock et al., 2008). While a major reduction in krill has been reported from the southwest Atlantic region between 1976 and 2004 (Atkinson et al., 2004), a linear trend in krill abundance was not detected in a 12-year time series from the WAP (Ross et al., 2008) – although Quetin and Ross (2009) provided preliminary evidence that populations of krill are declining in the Palmer LTER region in concert with an increasing delay in sea ice advance. Montes-Hugo et al. (2009) further concluded that the southward shift in large-cell phytoplankton abundance is expected to lead to a reduction in Antarctic krill abundance in the northern WAP region. Determining trends in krill abundance is, however, difficult due to spatial and temporal sampling constraints that under-sample cyclical population swings caused by recruitment variability (Quetin and Ross, 2003; Smetacek and Nicol, 2005). It is not known whether krill are increasing or decreasing elsewhere (Nicol, 2006), including in the Ross Sea sector where opposite changes are observed in sea ice advance and retreat (compared to the WAP region) (Stammerjohn et al., 2008a). Confounding factors are the effect of past harvesting on krill predators and their subsequent recovery as well as krill fishing (Ainley et al., 2007; Croxall and Nicol, 2004).

It has been proposed that in the WAP region, a strong relationship exists between Antarctic krill abundance/recruitment and winter sea ice extent i.e. larger krill populations associated with more extensive sea ice (Loeb et al., 1997). Similarly, Nicol et al. (2000) observed more krill where there was more sea ice off East Antarctica. Studies resolving seasonal changes in sea ice habitat (Ross et al., 2008) further indicate that the timing of seasonal ice advance and retreat, and the resultant duration of winter ice, affects habitat "quality" for krill (Quetin et al., 2007). A critical period is when sea ice advances in autumn at a time and location where larval krill ascend to surface waters, requiring food and refuge. A conceptual model put forward by Quetin and Ross (2009) is that the later the timing of annual sea ice formation, the lower the food availability to krill, and the lower the growth rates and predicted survival rates of juvenile krill in particular. In turn, the timing of spring sea ice retreat and its associated phytoplankton blooms are critical for adult female krill reaching optimal breeding condition. Thus, variability in seasonal sea ice "dynamics" (timing, duration and maximum extent) impacts food availability during critical periods of their life cycle and is a primary factor driving variability in year class strength or recruitment success (Quetin and Ross, 2009). Though there are indications that a shorter sea ice season (when coupled with an early ice retreat) is unfavourable for krill reproduction, it would favour salps (*Salpa thompsoni*) (Ross et al., 2008). The relative increase in salps has been attributed to the decrease in phytoplankton size spectrum associated with loss of sea ice (Moline et al., 2008). Such changes have major implications, given that salps are a much less nutritious and palatable food source for higher predators, and effectively represent a dead end in the food chain (Dubischar et al., 2006). Changes in sea ice deformation are also likely to be a factor affecting krill, given that thicker rafted ice provides a better refuge for juveniles in particular than thinner undeformed ice (Frazer et al., 1997; Ross et al., 2004; Massom et al., 2006).

Silverfish are also vulnerable to sea ice change. This species, which represents a crucial trophic link (Moline et al., 2008), is the most abundant fish in Antarctic coastal pelagic waters and the Adélie penguin's preferred food source. A disappearance of silverfish has been observed in the diet of WAP predators (Emslie and Patterson, 2007). This is again consistent with warming and a decrease of sea ice in that region, given the fish's apparent reliance on sea ice for spawning and as an early nursery (Vacchi et al., 2004). Further evidence of a decline of larval silverfish in the northern WAP region comes from Quetin and Ross (2009).

At a top predator level, numbers of sea ice obligate Adélie penguins (*P. adeliae*) at Palmer Station have

dropped dramatically over the past 25 years — by 65% — and are being replaced by chinstrap penguins (*Pygoscelis antarctica*) and gentoo penguins (*Pygoscelis papua*), which are Sub-Antarctic species adapted to warmer conditions and are ice-tolerant only (Ducklow et al., 2007) (Fig. 9). It is also thought that an increase in storminess (correlated with positive SAM index polarity (Lubin et al., 2008)) and snowfall during critical stages of the breeding season are key factors contributing to local Adélie penguin decline (Massom et al., 2006; McClintock et al., 2008). This is borne out by case-study evidence presented in the next section. Since gentoo and chinstrap penguins breed later, they are less affected by increased springtime snowfall (Ducklow et al., 2007). Other ice-mediated factors affecting penguin mortality and recruitment include ice-edge foraging in winter, foraging trip duration during spring breeding and food availability (i.e. krill and silverfish) to fledging chicks in summer (Fraser and Hofmann, 2003). The impact of fast ice on these key factors and relating to emperor penguins is briefly examined in Section 4.2.

Within the context of a "habitat optimum" model (Fraser and Trivelpiece, 1996), these changes in Adélie penguin populations suggest that adverse environmental conditions periodically breach critical life-history thresholds from which populations may not recover. Adélie penguin population trends in this region show a pattern of episodic, step-wise decreases with interim periods of relative population stability (cf. Fraser and Patterson 1997; Smith et al. 2003a). This highlights the critical importance of understanding life history strategies in terms of investigating linkages to climate change (Fraser and Trivelpiece, 1996; Fraser and Hofmann, 2003).

Regional differences also need to be factored in when assessing change. In the southern Scotia Sea at Signy Island, both Adélie and chinstrap penguins have decreased, while gentoo penguin numbers have increased (Forcada et al., 2006; Hinke et al., 2007). This pattern has been attributed to periodic warm events leading to reduced prey biomass due to changes in sea ice (Trathan et al., 2007). According to Forcada et al. (2006), variability in population sizes of these three species has reflected a local balance between trophic-mediated changes cascading from large-scale climate forcing and penguin adaptation (or lack of) to sea ice conditions. Forcada and Trathan (2009) have further shown an increase in variability of the environmental response in the north of the AP region, again highlighting the complexity of changes driven by large-scale atmospheric shifts.

The pattern is different again in the southwestern Ross Sea. There, breeding by an increasing number of adult Adélie penguins and a concomitant population increase has been attributed to optimal sea ice conditions in terms of consistent wind dissipation of coastal sea ice i.e. greater polynya formation (Ainley et al., 2005). Driven by switches in SAM, these conditions offer easier access to prey, particularly in spring.
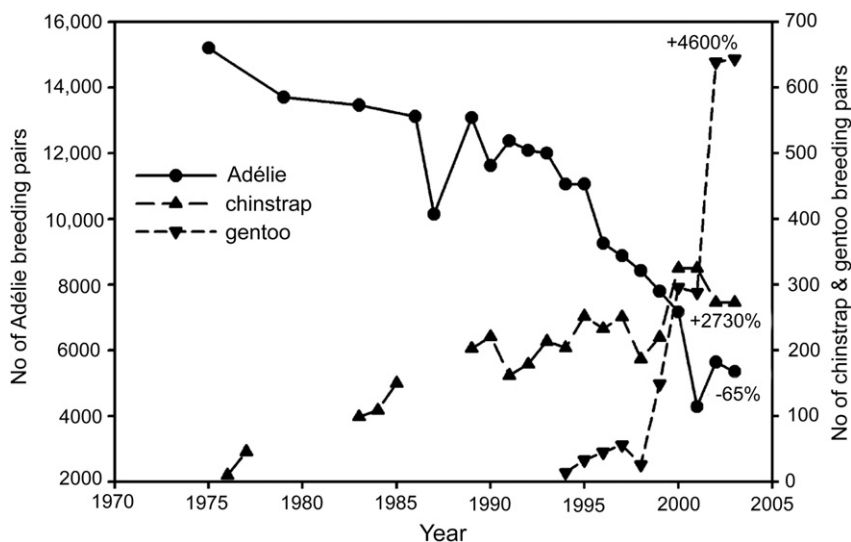

Fig. 9. Population trends for three penguin species in the vicinity of Anvers Island (West Antarctic Peninsula), 1975–2003. The numbers on the graph indicate percentage change from initial sampling year for each species. Gentoo penguin numbers in particular have sky-rocketed. From Ducklow et al. (2007).

The importance of regional differences is highlighted by the fact that Adélie penguin numbers are increasing in East Antarctica (at Dumont d'Urville and Casey) (Ainley et al., 2010). Forcada and Trathan (2009) offered an excellent overview of the complexities involved in penguin responses to climate change and variability in the Southern Ocean, and the challenges in unravelling these complexities and in predicting possible future responses.

Studies elsewhere around Antarctica have further highlighted the vulnerability of vertebrate populations (i.e. seabirds and Weddell seals (*Leptonychotes weddellii*)) to sea ice-related habitat changes in response to climate change and variability, including sub-decadal and decadal-scale changes and/or possible regime shifts in atmospheric forcing related to the Semi-Annual Oscillation (SAO) and SAM, e.g. Ainley et al. (2005), Barber-Meyer et al. (2008), Barbraud and Weimerskirch (2001, 2006), Croxall et al. (2002), Hadley et al. (2007), Jenouvrier et al. (2005a,b), Olivier et al. (2004), Proffitt et al. (2007), Weimerskirch et al. (2003), Wilson et al. (2001). These studies have largely examined correlations between population dynamics and fluctuations in broad-scale pack ice concentration and extent, and significant work remains to unravel exact linkages and the impact of changing sea ice seasonality outside the WAP region. Moreover, the vulnerability of vertebrates to changes in more localised environmental parameters, such as fast ice, are poorly understood. In the next section, we show that variability in fast ice distribution, which is itself a sensitive indicator of changes in oceanic and atmospheric circulation, has an immediate impact on Emperor penguin breeding success, amongst other things.

Issues relating to whales, sea ice and climate change are reviewed in Ainley et al. (2009), Nicol et al. (2008) and Simmonds and Eliott (2009). As with penguins and seals, whales are wide-ranging and long-lived predators that integrate the effects of environmental variability/change over large spatio-temporal scales. Given the lack of information, however, it is currently not possible to assess what effects recent changes in sea ice distribution and seasonality have had on ice-associated species such as minke whales (*Balaenoptera bonaerensis*), blue whales (*Balaenoptera musculus*) and killer whales (*Orcinus orca*) in particular. Once again, this is a challenging issue, given the combination of sea ice effects mediated through prey availability (notably krill), the possible loss of suitable sea ice habitat, and harvesting and/or recovery from harvesting. Moreover, and for vertebrates in general, it is difficult to reconcile

that a number of krill-dependent species (e.g. fur seals at South Georgia (Trathan et al., 2007) and humpback whales off East Antarctica (*Megaptera novaeangliae*)) have been increasing at almost maximal rates at the same time that krill declines are supposed to be happening (Smetacek and Nicol, 2005). At present, our ability to realistically predict cetacean response to changing sea ice conditions is undermined by gaps in our knowledge of ice characteristics that might define the sea ice habitat, or seasonal variability in the use of this habitat (Nicol et al., 2008). It can be stated, however, that whales are likely to be vulnerable to sea ice change e.g. diminution of polynyas, fewer leads and thin ice regions due to wind-driven ice convergence, loss of ice, and loss of krill. This is also true for seals closely associated with sea ice such as the krill-feeding crabeater (*Lobodon carcinophagus*) (Siniff et al., 2008). Once again, there are difficulties associated with detecting anything but very large changes/trends in crabeater seals, given current large uncertainties and the challenges involved in estimating abundance (Southwell et al., 2008).

Returning to lower trophic levels and the wider circumpolar domain, mean Antarctic productivity derived from satellite ocean colour data and a productivity model has shown a significant increase over the last decade (Smith and Comiso, 2008). The reasons for this remain obscure and, as Smith and Comiso (2008) suggest, may not be related to anthropogenic climate change. This is difficult to determine given the current short record length. Models have suggested a further increase under a climate warming scenario e.g. Arrigo and Thomas (2004), Behrenfeld et al. (2006), due to increased ocean stratification resulting from an increase in sea ice melting, although there is considerable uncertainty. But, as discussed above, spatio-temporal aspects of sea ice advance and retreat are also likely to play a crucial role (e.g. Quetin et al., 2007). In particular, timing of sea ice formation is crucial, since the earlier sea ice forms, the more sea ice algal biomass is usually incorporated. Moreover, earlier ice formation means greater total light availability for the ice algae to grow before mid-winter (when light levels at most relevant latitudes are too low for net primary production) (Fritsen et al., 1998; Raymond et al., 2009).

4.2. Fast ice

Compared to pack ice, relatively little is known about fast ice, its likely response to climate change, and the impact of this response. By virtue of its relative

stability and other characteristics, fast ice is of major importance as a habitat for micro-organisms (Deming, 2009; Lizotte, 2003) and sea ice algae (Satoh and Watanabe 1988; McMinn et al. 2000) and as a breeding platform for Weddell seals (Thomas and DeMaster, 1983) and emperor penguins (Kirkwood and Robertson 1997; Burns and Kooyman, 2001). Emperor penguins are long-lived species, are dispersed throughout the sea ice zone when not intimately associated with fast ice during each breeding season (May–December), and are thought to be an iconic bellwether and integrator of climate change/variability in that they are susceptible to short- and long-term changes in fast ice, pack ice and associated prey species distribution and abundance (Ainley, 1983; Ancel et al., 1992).

A recent study highlights the sensitivity of the long-studied emperor penguin colony at Pointe Géologie on the Adélie Land coast in East Antarctica to spatio-temporal variability in fast ice distribution related to changes in wind direction (Massom et al., 2009). As shown in Fig. 10a, this colony is surrounded by an extensive "buttress" of annual fast ice that can form a consolidated though highly variable barrier between the colony and nearest foraging grounds. Emperor penguins ideally require a stable fast ice breeding platform during their breeding season while having ready access to open water (food) (Ancel et al., 1992; Kooyman, 1993). A satellite-based analysis over the period 1992–1999 shows that greater than average fast ice extent can have a major deleterious effect on the breeding success of this colony by increasing the foraging distance from the colony e.g. in 1994 (Fig. 10b and c). Conversely, high rates of breeding success occur in other years e.g. 1993, when the distance to the nearest foraging grounds (open water) is minimal. These results suggest that shorter distances equate to more (shorter) foraging trips during the critical incubation and chick rearing period (June–December), less energy expenditure (a key factor after the extended adult fasting periods in particular), and thus greater feeding frequency of the brood. Again, the timing of fast ice formation, ephemeral breakouts and annual breakup is a crucial factor rather than simply ice extent alone, here relative to the critical incubation and chick rearing period (June–December). By the same token, the stability of ice holding fledging chicks is crucial, given that large mortality rates can occur if the ice breaks up too soon. The effect of changing fast ice conditions on penguin mortality, prey species and foraging success (as well as other demographic parameters) remains largely

unknown, but is likely to be significant and is under investigation. While emperor penguins are intimately associated with fast ice, another factor affecting the health of colonies is of course variability in the wider pack ice zone, given the wide dispersal of non-breeding birds and the impact of the pack ice on food availability etc. (Barbraud and Weimerskirch, 2001).

The substantial interannual variability in fast ice and "nearest distance" is primarily determined in this case by changes in the directional persistence and strength of the prevailing wind field, with more southeasterly-southerly winds leading to greater/more frequent fast ice breakout in the trough region to the NW of the colony and marked in Fig. 10a (Massom et al., 2009). Fewer trough breakouts occur, and more extensive fast ice persists, when more easterly winds prevail. Intriguing "snapshot" satellite images from the winter of 1963 show a far less extensive fast ice "buttress" than that observed in 1992–1999 (Massom et al., 2009). This has been attributed to a different wind regime in 1963 i.e. stronger winds from a more southerly direction compared to the long-term mean measured at Dumont d'Urville. Moreover, this coincided with the highest emperor penguin breeding success in the long-term record, and hints at a possible subsequent regime shift in regional atmospheric circulation.

Apart from local effect of wind, fast ice extent and "distance" in this region is also dependent on remote processes within the surrounding pack ice zone i.e. the presence/absence of a recurrent mid-pack "stream" of thick, consolidated ice and ice production from the Mertz Glacier polynya to the immediate east, as shown in Fig. 11 (Barber and Massom, 2007; Massom et al., 2001b, 2009). These are in turn affected by the coastal configuration of the ice sheet and distribution of grounded icebergs "upstream" i.e. 100s of kms to the east. It follows that predictions of future spatio-temporal changes in fast ice habitat should take into account not only changes in wind direction but also changes in remote processes and phenomena including ice sheet dynamics as it affects iceberg calving rates.

Elsewhere, a recent decline in Weddell seals in the vicinity of Palmer Station (in the WAP sector) appears to be due to a reduction in fast ice during the breeding season (Siniff et al., 2008). Siniff et al. (2008) suggest that pupping success for this species will in general be affected by changes in fast ice thickness or its spatio-temporal characteristics. In contrast, Emmerson and Southwell (2008) report a strong negative impact of extensive fast ice on Adélie penguin reproductive performance in certain East Antarctic colonies. They
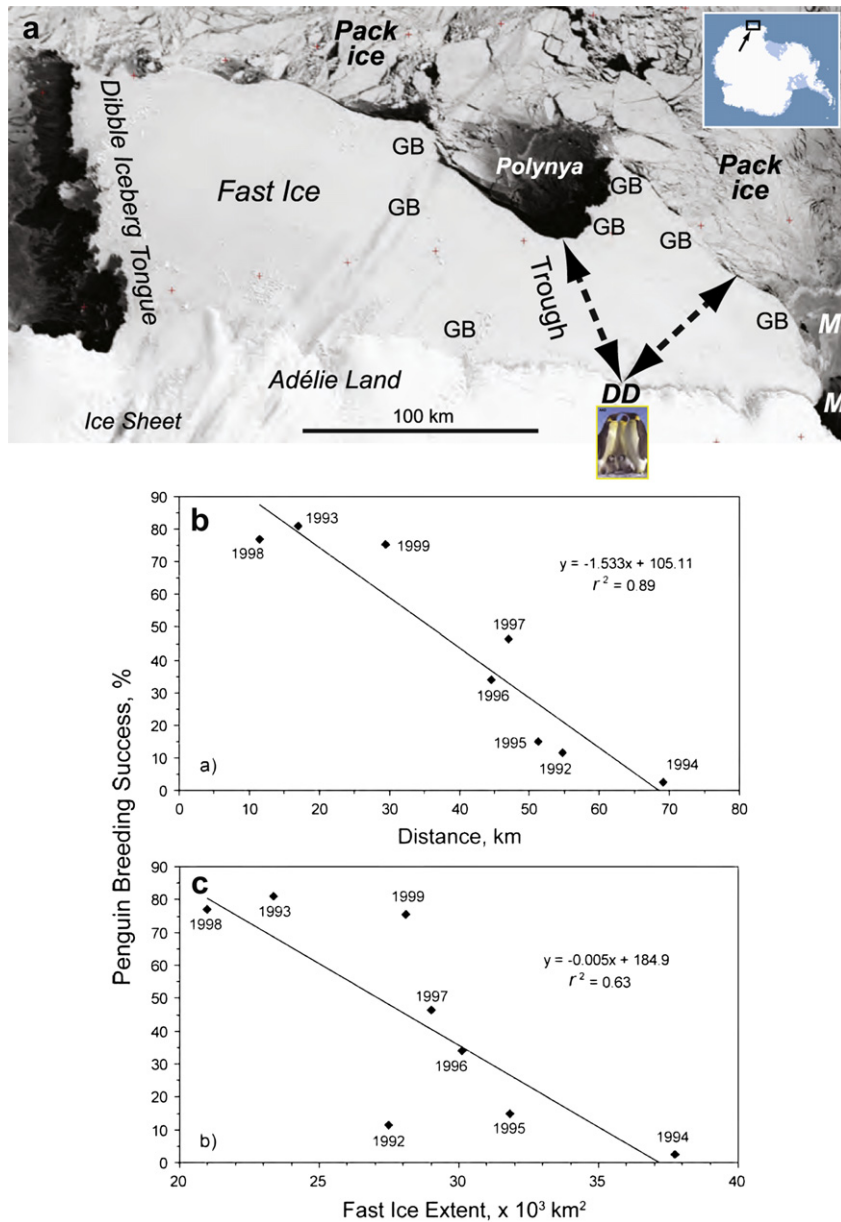
Fig. 10. a) A cloud-free MODIS satellite visible image (resolution 0.25 km) showing fast ice surrounding the emperor penguin colony at Pointe Géologie near Dumont d'Urville (DD). GB specifies the approximate location of assemblages of small grounded icebergs produced by local outlet glaciers, while M is the western part of the Mertz Glacier polynya. The dashed lines signify nearest distance between the colony and open water/foraging. Scatter plots of emperor penguin breeding success ([no. fledged chicks in late November]/[no. of breeding pairs] × 100) for 1992–1999 versus (a) shortest straight-line distance between the colony and the nearest open water, and (b) extent of the fast ice buttress, both averaged over the June to December period and with linear regressions applied. The r^2 correlation of fast ice extent and distance versus breeding success is 0.63 and 0.89 respectively. After Massom et al. (2009).

conclude that prediction of Adélie penguin population change relative to changes in sea ice habitat may be complicated by the fact that penguin–ice interactions vary according to the type of ice present and the processes contributing to population change that are influenced by sea ice. This important statement could equally be applied to other vertebrates and organisms associated with sea ice, especially given our lack of understanding of the exact nature of the links between organisms and different characteristics of the ice.
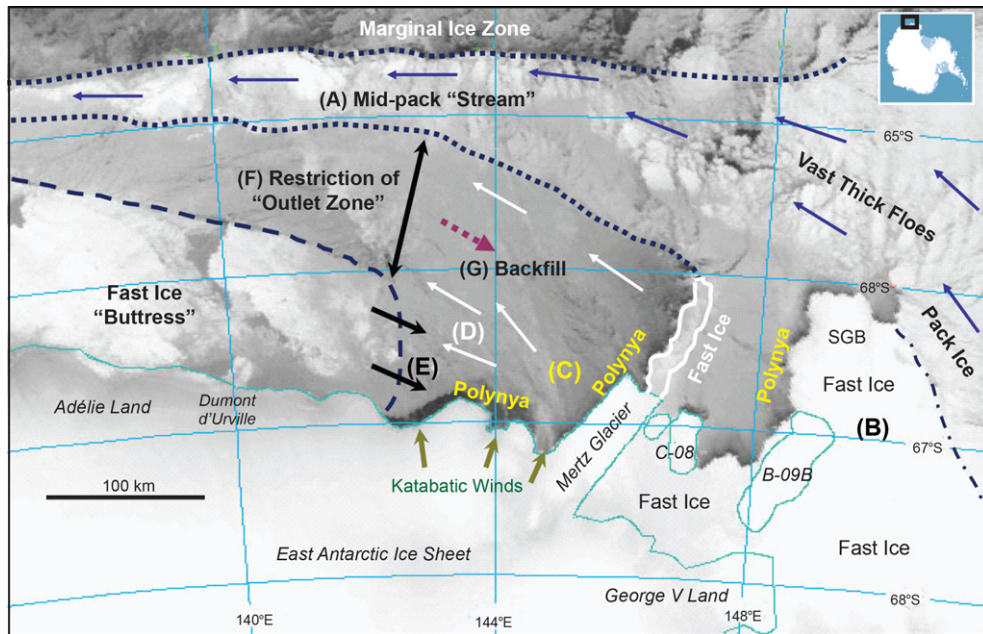
Fig. 11. Cloud-free NOAA satellite Advanced Very High Resolution Radiometer thermal infrared image from 14 June 1999, showing the complex interactions and interplay that occur in the East Antarctic coastal zone from ~135 to 152°E. A coherent "stream of vast thick floes (marked A) typically forms mid-pack as a result of the northward deflection of sea ice drifting westwards within the Antarctic Coastal Current by a major promontory (B) of fast ice, small grounded icebergs (SGB – see Fig. 3b) and large grounded icebergs combined. This recurrent feature flows westwards along the shelf break to effectively enclose the Mertz Glacier Polynya (C) and the fast ice "buttress" surrounding the Pointe Géologie emperor penguin colony, to protect the fast ice from southward penetration of destructive swell from the open ocean. The northward extent of the fast ice "buttress" tends to be less when the "stream" is absent (Massom et al., 2009). Sea ice formed in the Mertz Glacier polynya "ice factory" and drifting westwards (D) is intercepted by the eastern margin of the buttress. In this manner, the polynya contributes to the eastward migration of the fast ice (E), to effectively close off the western part of the polynya. The "buttress" and "stream" further combine to restrict the outlet for sea ice formed within the polynya (F). This can in lead to a "backfilling" of the polynya (G) to temporally diminish its size and efficacy as an ice production "factory", which it turn affects its contribution to the buildup/maintenance of the fast ice "buttress". Ice in this polynya "regime" is preferred habitat for crabeater seals in winter (McMahon et al., 2002). Adapted from Massom et al. (2001a).

4.3. Polynyas

To date, there has been no evidence of any clear trends in winter-time polynya areal extent over the satellite passive microwave era (Kern, 2009). A major concern, however, is if the major polynyas decreased in size, there could be serious impact on regional sea ice production; the ocean freshwater budget and global thermohaline circulation (and thus climate) (Rintoul, 2007); and regional primary production. A key factor in this respect may be the predicted decrease in katabatic wind strength over the coming decades (Mayewski et al., 2009). Current research is investigating possible links between changes in the Ross Ice Shelf Polynya (and other nearby polynyas) and the observed freshening of High Salinity Shelf Water (HSSW) that contributes to AABW formation (Jacobs, 2006; Jacobs et al., 2002). Martin et al. (2007) suggest that the annual polynya area and associated sea ice production increased over the period 1992–2002

(which would increase HSSW salinity). Therefore, the HSSW salinity decrease is likely due to changes in the properties of water flowing into the Ross Sea. According to Tamura et al. (2008), on the other hand, the polynya area and annual cumulative sea ice production decreased in the Ross Ice Shelf Polynya over 1992–2001, the latter by ~30% from the 1990s to the 2000s, thus contributing to the observed ocean freshening (along with atmospheric warming and greater input of glacial meltwater). This large polynya decrease has been attributed to the grounding of vast fragments of iceberg B-15 alongside the western Ross Ice Shelf in 2000. Ecological impacts of this grounding are discussed in Section 7.1.

The regional influence of another major polynya – that adjacent to the floating Mertz Glacier tongue (MGT) at ~140°E – may change due to the calving in February 2010 of 78 km (or ~80%) of the glacier tongue. This has significantly changed the area of the polynya, which currently accounts for only 0.001% of

the total winter sea ice area but 1% of total annual sea ice production (Tamura et al., 2008). Ecological impacts are also expected to be significant, given the fact that the MGT polynya is a major regional "hot-spot" for primary production (Arrigo and van Dijken, 2003), influences the extent of fast ice surrounding the important emperor penguin colony at Pointe Géo-logie (see above) and greatly affects the timing and seasonal meltback of the regional pack ice (Massom et al., 1999). This event underlines the importance of the strong coupling that exists between the ice sheet coastal margins and sea ice.

5. The significance of extreme events

While much emphasis is often placed on climatic trends and their impacts, a description of events in the WAP region from October 2001 through February 2002 highlights the importance of "extreme" anomalies and the mixed ecosystem response to the multivariate changes in sea ice (see Massom et al., 2006 for details). We elaborate on this here as extreme events may become increasingly prevalent around Antarctica due to predicted increases in storminess with changing climate e.g. IPCC (2007). The key to the 2001/2 "event" was the persistence of a strongly positive atmospheric-pressure anomaly in the South Atlantic coupled with strong negative anomalies in the Bellingshausen–Amundsen and SW Weddell Seas (Fig. 12a). This configuration, which formed a component of a persistent hemispheric wave number three pattern, created a prolonged period of strongly, warm and moist northwesterly winds blowing across the Bellingshausen Sea ice cover (Fig. 12b and c). Northerly winds are not uncommon in transporting warm air across the Antarctic sea ice zone, but they typically occur over periods of 1–2 days with the passing of storms (Massom et al., 1997). What was unusual about the 2001/2 "event" is that it lasted fully 5 months or so, and had a profound effect on regional sea ice and ocean conditions and thus marine ecology from early spring through summer.

This impact was highly complex, and indeed para-doxical, with counteractive processes and phenomena occurring simultaneously or in succession (Massom et al., 2006). These included:

- Simultaneous sea ice dynamical thickening (up to 20 m, Fig. 12d) and extensive surface melt, driven by strong, warm northerly winds during late winter-early spring;
- A strong negative sea ice extent anomaly offshore from the West Antarctic coast in late winter-early

spring (Fig. 12b) followed by a strong positive sea ice anomaly inshore during summer (Fig. 12c) caused by the wind-driven rapid spring sea ice retreat creating a thick, highly compact coastal sea ice zone that subsequently survived the summer melt season;
- Increased snowfall under blizzard conditions, associated with warm, moisture-laden northerly winds, blowing over a greater expanse of open ocean, resulting in an anomalously thick snow cover;
- Increased snow loading, enhanced ice deformation and ice permeability (due to the warm tempera-tures) led to widespread flooding of the snow/ice interface (Fig. 12e), resulting in enhanced snow-ice formation (i.e. freezing of slush at the ice surface) during intervening cold snaps.

The biological and ecological response to these atmospherically-driven environmental conditions was complex and both negative and positive (Massom et al., 2006). The extensive ice-surface flooding led to a major elevation of nutrient levels and a high concentration of algal biomass (up to ∼222 mg chl-a m^3 compared to ∼0.2 mg chl-a m^3 in the underlying upper water column). Subsequent mechanical pulver-isation of this ice by strong wave–ice interaction (driven by the persistent northerly winds) led to an extensive and intense phytoplankton bloom within the highly-compact marginal ice zone (over a width of tens of kilometres), relatively early (mid-October) and far south (Fig. 13a). Thus, a major bloom occurred within a 100% sea ice cover and coincided with a major negative ice extent anomaly in the region. This repre-sented coincident positive and negative phenomena from a krill perspective, and was contrary to conven-tional wisdom i.e. extensive sea ice leads to greater blooms.

Satellite remote sensing of ocean colour cannot detect intra-ice, or under ice, algal blooms, so the October 2001 bloom went undetected by SeaWiFS (Fig. 13b). But, starting in late October 2001, the outer pack ice began to breakup and release the "biological soup" into the open ocean that in turn contributed to the largest positive chl-a anomaly in the WAP region over 1997–2004. This highlights a major unknown, namely algal biomass and production within the sea ice itself. A large concentration of wildlife was observed at and within the ice edge (in mid-October), associated with the intra-ice algal bloom. This included groups of snow petrels (*Pagodroma nivea*), Antarctic petrels (*Thalassoica antarctica*), chinstrap and Adélie
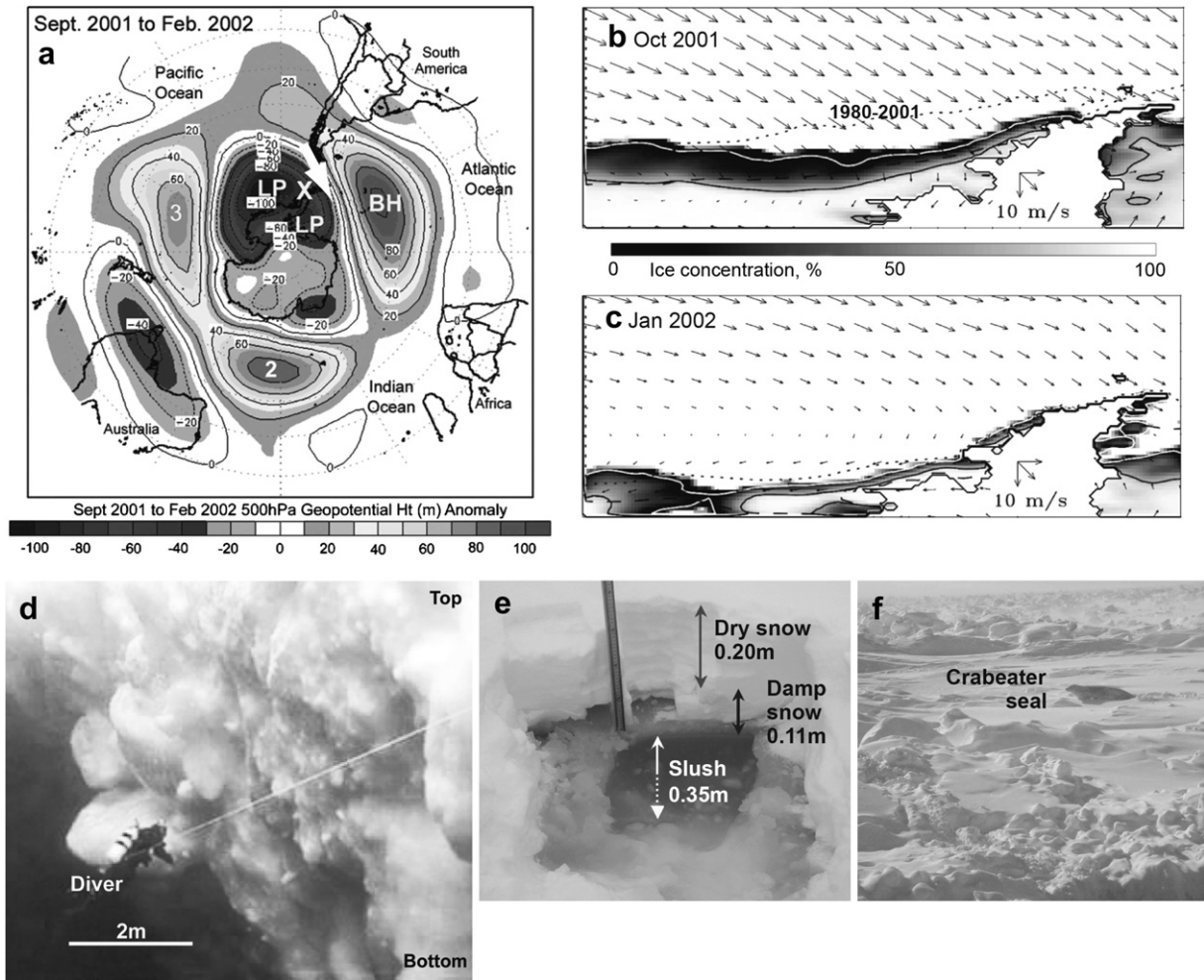
Fig. 12. a) Monthly mean composite anomaly map of NNR 500-hPa geopotential height for the Southern Ocean and Antarctica for September 2001 through February 2002 (relative to the mean September–February 1980–2001). BH and LP denote the high pressure (positive or blocking-high) and low-pressure (negative) anomalies, respectively. X is the approximate location of the September–October 2001 field experiment, with the white arrow showing the dominant direction of prevailing winds across the WAP region. b) and c) Maps of monthly mean DMSP SSM/I sea ice concentrations in the WAP region from October 2001 and January 2002, with 15% and 75% ice concentration contours marked (the white and black lines, respectively). The long-term means (1980–2001) of the locations of the 15% and 75% ice concentration contours for each month are marked as black dotted and black dashed lines, respectively. Contemporary monthly mean wind velocity data from the NNR dataset are superimposed, showing the dominant northerly airflow across the region. d) Vertical wall of sea ice ∼20 m thick and comprising rafted blocks of first-year sea ice. e) Flooding of the snow-ice interface (example from September 27, 2001), creating a layer of slush 35 cm thick (below sea level) and subsequently leading to snow-ice formation. f) Heavily consolidated thick first-year ice with a heavily deformed top and bottom surfaces, with a crabeater seal in background. All photographs from Marguerite Bay, Bellingshausen Sea, September–October 2001. After Massom et al. (2006).

penguins, Antarctic terns (*Sterna vittata*), crabeater seals (*L. carcinophagus*), leopard seals (*Hydrurga leptonyx*) and killer whales. This example paradoxically shows that the sea ice zone can "seed" significant spring-time phytoplankton blooms even following an anomalously low sea ice extent, and underlines the key role of wave–ice interaction processes. It also highlights the key "preconditioning" role played by the prevalence of more northerly winds.

On the negative side, the extreme ice compaction created heavy ice conditions with few leads (Fig. 12f) that deleteriously affected the ability of top predators (whales/seals/penguins) to locate and access prey, traverse the sea ice zone, access air to breath and haul out. It also led to diminution of the areal extent of krill sea ice habitat compounded by an early sea ice retreat. However, it also created an ice cover composed of a mass of rafted first-year floes, with individual floes <1 m
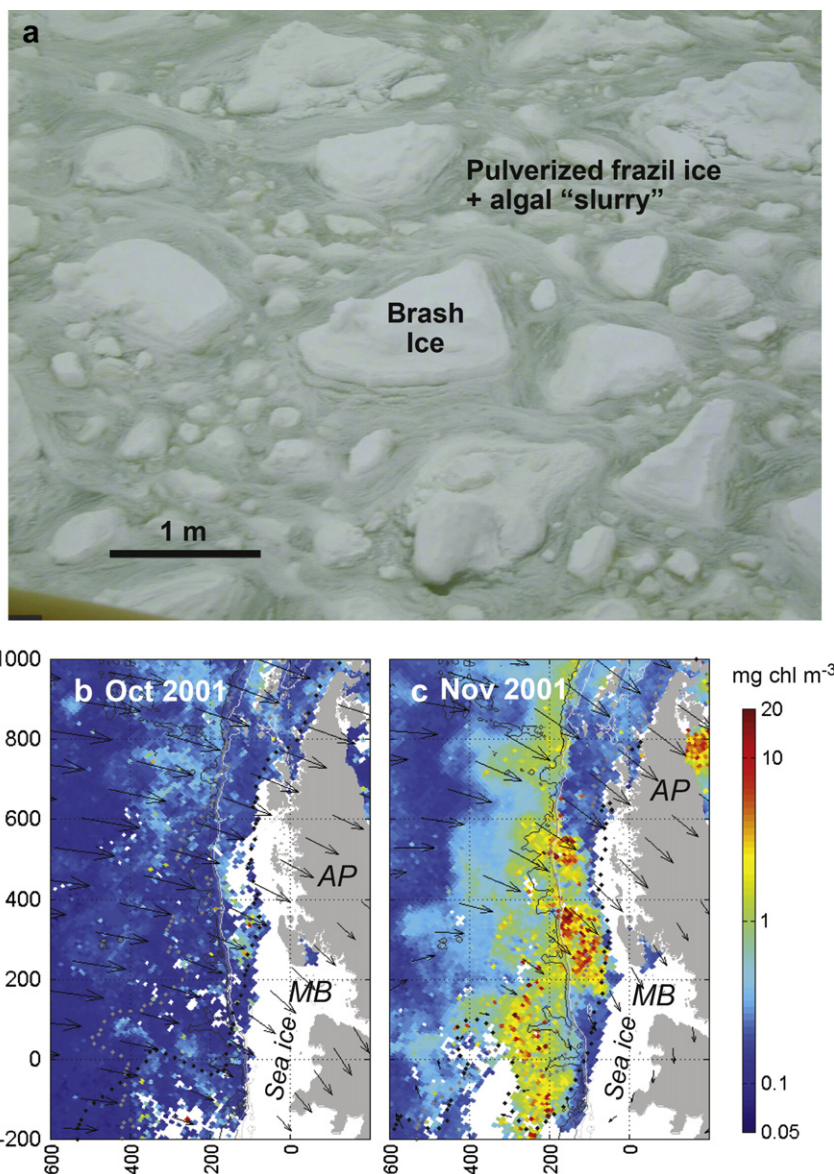
Fig. 13. a) Photograph taken from the deck of the R/V *Nathaniel B. Palmer* in the marginal ice zone of the Bellingshausen Sea in mid-October 2001, showing the high proportion of frazil ice and algal "slurry" (green) between fragments of brash ice in the highly-compact marginal ice zone formed by pulverisation of the ice by intense wave–ice interaction. Monthly-averaged SeaWiFS images of the WAP region for b) October 2001 and c) November 2001, showing pigment biomass in mg chl m^{-3} (log scale). Sea ice is masked white, and monthly-averaged NNR wind vectors are shown as black arrows. AP is the Antarctic Peninsula and MB is Marguerite Bay. Dimensions are in kilometres. After Massom et al. (2006).

thick separated by water-filled gaps (Fig. 14a and b). This in part created a positive ecological effect, given that ice-rafted gaps serve as ideal habitat for larval krill by providing a refuge from predators, a food repository, and a relatively quiescent (less turbulent) environment (Frazer et al., 1997; Marschall, 1988). However, compared to other years, larval krill growth was zero to negative over the September–October 2001 period (Fig. 14c). This has been attributed to

insufficient food availability within a very thick sea ice cover composed of deeply rafted blocks (despite large numbers of larval krill observed feeding on the floors, sides and "caves" of the more shallow rafted blocks) (Quetin and Ross, 2009). While over-rafted pack ice is a favoured habitat for krill, the year of 2001 may have been a case of too much of a good thing, where quality decreased with increasing quantity at depth. This again emphasises that there is more
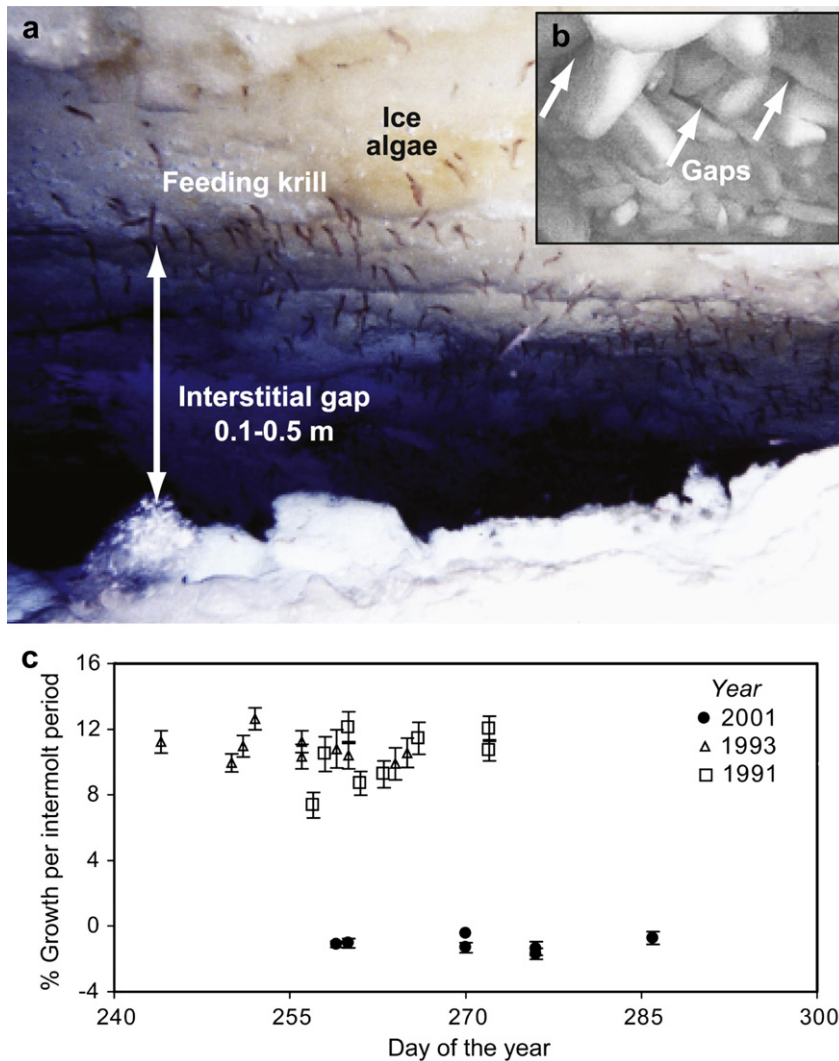
Fig. 14. a) Photograph of "gap" habitat in Antarctic sea ice, looking horizontally into the gap and showing krill feeding on the ice algae on the "ceiling" or underside of an ice block (photograph courtesy Alfred Wegener Institute). b) Photograph of the underside of the ice showing gaps between the rafted blocks of first-year sea ice, Marguerite Bay, October 2001 (photograph courtesy Langdon Quetin, University of California Santa Barbara). c) Plot of *in situ* growth increments (% growth per intermoult period) for larval Antarctic krill collected from under the ice in the austral springs of 1991 (open squares), 1993 (open triangles), and 2001 (closed circles). Larvae collected in 2001 averaged from 9.6 to 11.1 mm in total length. Points represent the mean growth increment for an experiment comprising 7–15 measurements, error bars are standard error. After Massom et al. (2006).

to consider when modelling and evaluating the ecological impact of changing sea ice conditions than sea ice extent alone (Quetin et al., 2007). In this case, degree of deformation and availability of shallow rafted (light-filled) gap habitat are key contributing factors, as is food availability.

The persistent heavy sea ice conditions combined with anomalously heavy snowfall in spring also contributed to a disastrous Adélie penguin-breeding season at Anvers Island (∼64.04°S, 64.46°W) in

2001/2 (this is the colony that has been declining). Up to that time, it was the lowest breeding success, with 0.78 chicks versus a long-term mean of 1.35 chicks crêched per breeding pair, and the largest between-year population decrease (40%) in the 28-year record (see Fig. 9). Moreover, peak fledging for the chicks that survived took place one week later relative to the long-term average. This corresponded to an equal delay in peak egg laying. Causal factors included nest flooding and drowning of eggs and small chicks due to

enhanced snow accumulation and springtime melt; and heavy sea ice conditions forcing large numbers of birds to delay breeding or induced winter adult mortality.

Not all anomalous events can be attributed to SAM. While the extreme "event" in 2001/2 was associated with a strongly positive SAM index (Massom et al., 2006), similar ice compaction and snowfall conditions occurred in September–October 2005 that were associated with the occurrence of a weak La Niña (while SAM was near neutral), with a quasi-stationary zonal wave three pattern again dominating hemispheric atmospheric circulation (Massom et al., 2008). Amongst other things, extreme sea ice compaction led to a sign change in monthly sea ice extent anomaly from negative to positive with the transition from spring to summer in 2005/6. This work again underlines the key importance of wind-driven ice dynamics in recent changes in the WAP (see also Harangozo, 2006; Stammerjohn et al., 2008b) and shows a statistically-significant increase in September northerly 10-m winds between 110 and 125°W over 1979–2005.

6. Future large-scale sea ice coverage – Model predictions

Although large discrepancies exist between individual General Circulation Models (GCMs) in their ability to simulate/replicate current Antarctic sea ice concentration/extent and thickness distributions (Fichefet et al., 2008; Parkinson et al., 2006; Lefebvre and Goosse, 2008), there is general agreement in model projections that a substantial loss of Antarctic sea will occur over the 21st Century (IPCC, 2007). Indeed, an ensemble average across 15 models analysed by Arzel et al. (2006) shows that winter sea ice extent and volume will decline by 24% and 34% respectively by the year 2100. According to the weighted average given by Bracegirdle et al. (2008), there will be an overall decline of 33% in total sea ice area in winter. Regions of greatest sea ice change are shown in Fig. 15, depicting results from the CSIRO Mk3.5 model (one of the better performing models). While greater overall coverage is predicted in summer (Fig. 15c versus a), large uncertainty is associated with known issues in model performance during this season (Arzel et al., 2006). The sectors showing the greatest winter sea ice declines will be the Bellingshausen and Amundsen seas – sectors which already show considerable declines during the current epoch (Figs. 5 and 6) linked to changes in the high-latitude response to ENSO variability and a more positive SAM.

Substantial sea ice declines are also predicted in the northeastern outflow region of the Weddell Gyre (over 60°W–70°E). These changes translate to a decrease in amplitude of the seasonal cycle (SSIZ) – with major ecological implications as discussed above. Further, it has been suggested that the current increasing trend in overall Antarctic sea ice extent is linked to the depletion of springtime stratospheric ozone, and that significant declines in sea ice are likely in the future as ozone levels recover and the impact of increasing greenhouse gases becomes more pronounced (Turner et al., 2009b).

Accurate and reliable prediction of future sea ice changes are a key to predicting and managing the high-latitude Southern Ocean ecosystem (using ecosystem models) (Murphy et al., 2008). Moreover, although GCMs suggest a rapid decline in Antarctic sea ice thickness (Fig. 15), we have currently no observations with which to assess whether sea ice thickness has changed or is changing. Satellite altimetry offers the only practical means of measuring and monitoring Antarctic sea ice thickness on regional scales (Giles et al., 2008b; Zwally et al., 2008), but this requires independent knowledge of snow thickness and density. Validation is crucial, and is currently underway.

A recent study by Jenouvrier et al. (2009) explicitly links the predicted decline in Antarctic pack ice coverage to forecasted population decreases of the Emperor penguins in Adélie Land. Basing their results on 10 IPCC (2007) climate models, they predict that, by 2100, this population will decline dramatically (from ∼6000 to ∼400 breeding pairs) to near-extinction in response to decreasing pack ice coverage and associated greater frequency of warm events over the region. Jenouvrier et al. (2009) conclude by stating that as the Antarctic warms, the Ross Sea may become the last bastion for Emperor penguin populations. The populations in the Ross Sea region, which are the southernmost of all and comprise ∼25% of the total world population, are currently stable (Barber-Meyer et al., 2008) – a factor which has been attributed to the increasing pack ice coverage there (see Figs. 5 and 6). Similarly, Ainley et al. (2010) concluded that 70% of the Antarctic Adélie penguin population (75% of colonies) and 40% of the Emperor penguin population (50% of colonies) are in jeopardy of marked decline/disappearance by 2100 due to the decline in sea ice coverage and thickness predicted by an ensemble average of IPCC AR4 climate models.

By concentrating only on pack ice extent, the Jenouvrier et al. (2009) study failed, however, to account for fast ice changes and the associated possible
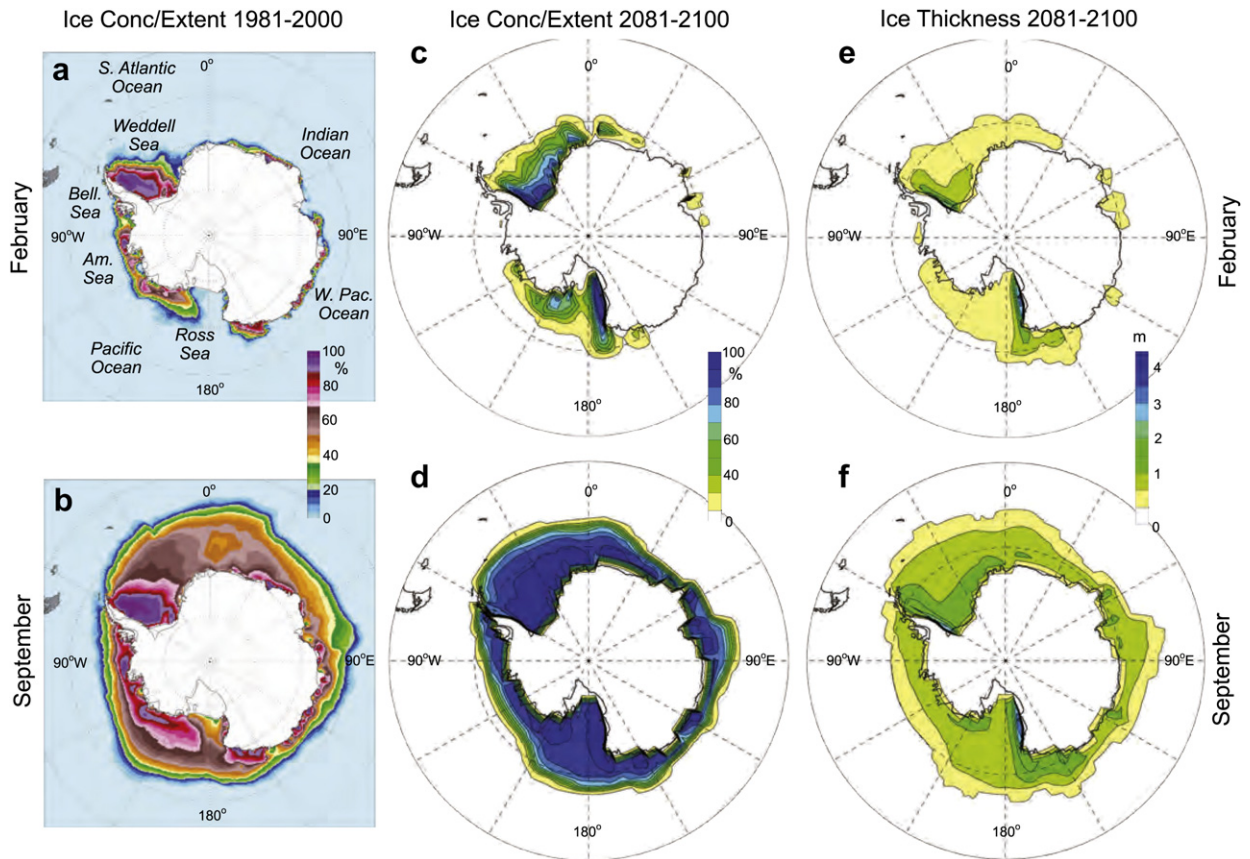
Fig. 15. a), b) Maps of satellite-derived mean (1981–2000) sea ice concentration for February and September, using NASA Bootstrap algorithm data from the US NSIDC (Comiso, 1999; http://nsidc.org/data/nsidc-0079.html). c), d) Modelled sea ice concentrations for the CSIRO Mk3.5 SRESA1B (mid-range) scenario for February and September for the period 2081–2100. e) and f) Modelled sea ice thickness (in m) for the CSIRO Mk3.5 SRESA1B scenario for February and September for 2081–2100. Some areas of bias are known in the model results, e.g. in the western Ross Sea; these arise from errors in oceanic and atmospheric forcing. Model results after Massom et al. (in preparation), courtesy Siobhan O'Farrell (CSIRO).

impact on future penguin demographic parameters under a climate-change scenario. While overall pack ice is undoubtedly important, not least in terms of its impact on non-breeding birds, it was shown earlier that fast ice has an immediate effect on breeding success of the Adélie Land Emperor penguins (Massom et al., 2009). A critical factor that may contribute to the relative neglect of fast ice is that the resolution of GCMs is far too coarse to resolve the relatively narrow (yet crucially important) band of ice that skirts the Antarctic coastline. As a result, there have been no model predictions of fast ice response to the IPCC (2007) climate-change scenarios. Additional factors that may contribute to penguin population decline/stability include snowfall amount (Bricher et al., 2008), the degree of storminess/number of blizzards during critical periods in the breeding cycle (this also applies to Adélie penguins (Ducklow et al., 2007)), the degree

of human disturbance (Bricher et al., 2008; Woehler et al., 1994) and whether the pack-ice cover is divergent or convergent as it affects open water availability (Massom et al., 2006). As stated by Forcada and Trathan (2009), penguin responses in the wider circum-Antarctic are difficult to predict given the lack of understanding of climate effects on the complete life cycle. Moreover, there appears to be considerable regional variability in recent demographic and population dynamics responses to changing sea-ice characteristics (Ainley et al., 2010).

7. Possible future scenarios

In this section, we discuss possible future scenarios of ecological impacts (conceptual only) related to changes in fast ice and snowfall increases over the sea ice zone.

7.1. Increased number of icebergs

One of the predicted effects of continued global warming is an increase in the discharge of continental ice into the sea from outlet glaciers and ice shelves around Antarctica (Bentley et al., 2007). Any resultant increase in the number of icebergs within the coastal zone (and beyond) could have major impacts on local-regional sea ice conditions and associated biological processes. Positive (and paradoxical) impacts could include more extensive fast ice given its strong association with grounded icebergs (with implications for emperor penguins etc. – see above), although other factors could also come into play e.g. changes in wind direction/strength, pack ice spatio-temporal characteristics (see Fig. 11), ocean waves, and changes in ice sheet coastal configuration (Massom et al., 2009). Another positive ecological outcome could be the enhanced generation of "hotspots" for biological and chemical enrichments adjacent to icebergs (both drifting and grounded) due to localised meltwater and micro-nutrient inputs (see Smith et al., 2007) and the creation of lee polynyas (see Fig. 1) – with a substantial cumulative effect given the vast number of icebergs in the Southern Ocean. Clearly, there is a need for more information on iceberg calving and drift, residence and dissolution rates.

Negative effects of an increase in iceberg numbers could also be twofold. When they calved from the Ross Ice Shelf in 2000, vast fragments of iceberg B-15 subsequently grounded alongside Ross Island. This reduced regional primary production by an estimated 40% (by greatly reducing the areal extent of the highly-productive Ross Sea polynya) (Arrigo et al., 2002). It also greatly reduced the breeding success and survival of emperor and Adélie penguins in colonies adjacent to the grounded icebergs (Kooyman et al., 2007). Moreover, the number of breeding Weddell seals declined and fewer pups were born (Siniff et al., 2008). The impact on the Ross Sea polynya is shown in Fig. 16. Iceberg scour is also a major source of disturbance to benthic communities in waters shallower than ∼500 m (Gutt and Starmans, 2001), and this effect would presumably intensify with the calving of more icebergs. Having said this, fast ice would have the effect of locking in icebergs to restrict their movements (when ungrounded) and their potential to cause benthic disturbance (Smale et al., 2007).

Whereas large icebergs calvings are a "wildcard" in the system, the myriads of small icebergs produced by hundreds of outlet glaciers are equally important in their regional and cumulative impact. Recent ice shelf "disintegrations" in the Antarctic Peninsula region e.g. Larsen A in 1995 and B in 2002 (Scambos et al., 2003) and the Wilkins Ice Shelf in 2008–2009 (Scambos et al., 2009), have produced thousands of such icebergs to affect a large area of the deeper ocean. The disintegration of ice shelves also produces new habitat in the form of polynyas and sea ice where there was previously ice shelf e.g. the former Larsen B Ice Shelf region (Bertolin and Schloss, 2009). The biological impact of such events is only just emerging, but appears to have been rapid. For example, Bertolin and Schloss (2009) found high phytoplankton production and biomass values in newly open areas following the Larsen A collapse, suggesting its importance for biological pumping of CO_2. Moreover, Peck et al. (2009) estimated that, over the past 50 years, the loss of ice shelves and retreat of coastal glaciers around the Antarctic Peninsula has exposed at least 24,000 km^2 of new open water that was rapidly colonised by new phytoplankton blooms, with new benthic and marine zooplankton communities also being created. They further suggest that this is of climatic significance as a new carbon sink.

Another factor coming into play is the increase in freshwater input into the coastal zone from enhanced basal melt of outlet glaciers and ice shelves (Rignot et al., 2008). This impact is largest in the very region experiencing the greatest sea ice decline and warming i.e. the Amundsen/Bellingshausen Sea sector of West Antarctica. According to Dierssen et al. (2002), the glacial meltwater input can affect the regional hydrography in the WAP up to 100 km offshore, leading to increased water column stratification/stability and affecting water turbidity. They further suggest that changes in the seasonality and extent of the glacial meltwater plume have implications for both the functioning of the biota and the formation of sea ice. Regarding the latter, reduced sea ice will cause less stratification when it melts, although less sea ice formation reduces deep ocean mixing in autumn.

7.2. Increased storminess/waviness

A continuation of the observed poleward shift in storm tracks over the Southern Ocean has been predicted, leading to increased winds over the ocean (particularly in summer and autumn) (Turner et al., 2009a). This prediction has been attributed to the continued increase in greenhouse gas emissions combined with recovery of the ozone hole (Bracegirdle et al., 2008; Turner et al., 2009b). Storm activity (both local and distant) drives ocean wave generation and wave–ice interaction.
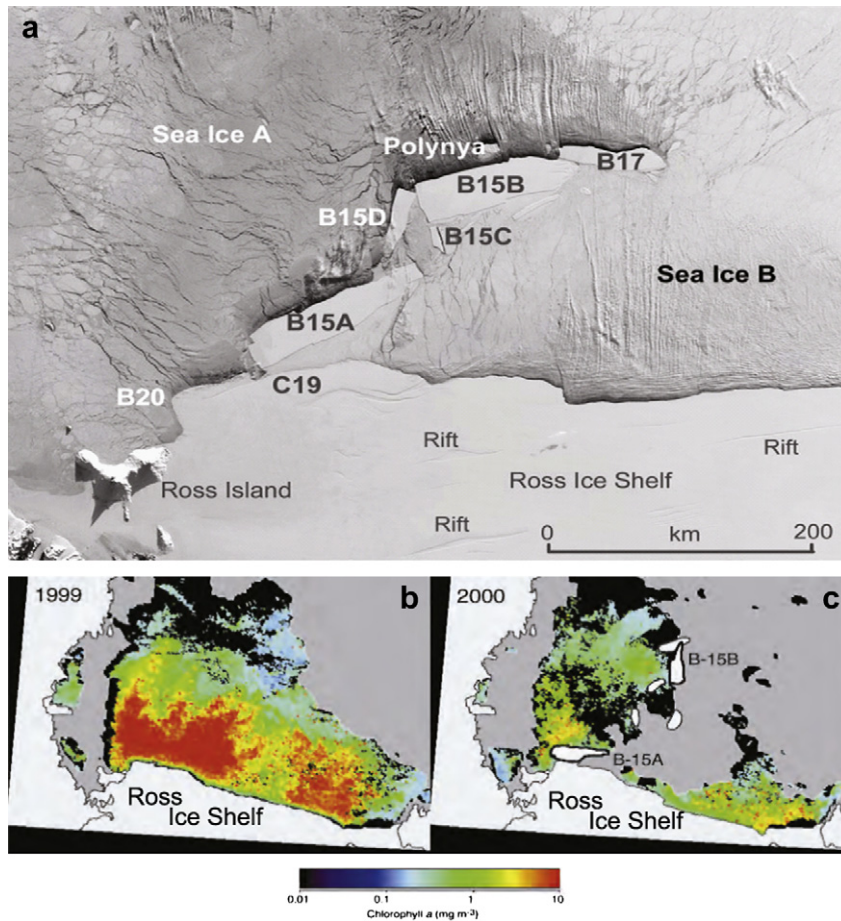
Fig. 16. a) MODIS visible satellite image (courtesy NASA) from 17 September 2000 showing the grounding of vast icebergs in the western Ross Sea adjacent to major penguin colonies in the vicinity of Ross Island, and their impact on regional sea ice dynamics that greatly diminished the areal extent of the Ross Ice Shelf polynya. Sea ice A denotes the polynya regime, while B is consolidated pack. b) and c). Mid-December distributions of pack ice (grey) derived from satellite passive microwave data and chlorophyll *a* concentrations from SeaWiFS for 1999 and 2000 respectively. Six large fragments of iceberg B-15 are shown in white in (c). After Arrigo et al. (2002).

Given these factors, it is suggested that the predicted increased windiness (Bracegirdle et al., 2008) and storminess at high southern latitudes (IPCC, 2007) could result in an increase in:

- Snow cover removal and floe surface flooding to result in more extensive surface "pond" communities (a positive ecological impact);
- The prevalence of "extreme" events, with both positive and negative impacts such as those described in Massom et al. (2006);
- Pancake ice formation, resulting in greater incorporation of biological material into the frazil ice matrix (versus columnar ice formed under more quiescent conditions) (positive);
- Fragmentation and pulverisation of existing floes (negative or positive, depending on the trophic level); this would combine with more widespread surface pond formation (decrease in albedo) to result in more rapid seasonal meltback of the ice cover in spring—summer (potentially negative), and could also lead to increased prevalence of intra-ice phytoplankton blooms as illustrated above (positive);
- Width of the marginal ice zone, which is a key ecological zone (positive);
- Fast ice breakup/lack of stability (negative, e.g. for breeding emperor penguins and Weddell seals); and
- Annual primary production in the Southern Ocean (positive), due to increased nutrient upwelling driven by stronger winds (Arrigo et al., 2008).

These would be some of the possible snow and sea ice-related changes in response to increased storminess

and wave generation, but there also would be changes affecting ocean structure, circulation, water mass distribution and air-sea gas exchange. Together these changes would affect ecosystem structure and biogeochemical cycling, with current evidence suggesting trends towards a weakening of the Southern Ocean carbon sink (Le Quéré et al., 2007; Lovenduski et al., 2007; Lovenduski et al., 2008; Doney et al., 2009a; Gruber et al., 2009) and increased ocean acidification (e.g. Doney et al., 2009b) leading to detrimental carbonate conditions for some plankton with potential food web consequences.

7.3. Increased snowfall/accumulation

Snowfall has increased on the western side of the Peninsula (van den Broeke et al., 2006), but whether changes have occurred elsewhere over the pack ice (Maksym and Markus, 2008) and coastal zone (Monaghan et al., 2006; Rignot et al., 2008) is less clear due to the vast areas involved and the difficulty of accurately measuring/estimating snowfall/accumulation in the windy Antarctic environment. However, an increase in precipitation over the high-latitude Southern Ocean has been predicted by GCMs for the coming decades (e.g. Bracegirdle et al., 2008), with larger winter than summer precipitation. Such an increase, which is likely to occur under windier and more stormy conditions with the expected southward migration of the mid-latitude storm track (Turner et al., 2009a), would have the following potential implications and effects (none of which are mutually exclusive and with the sign of possible impacts in parentheses):

- A reduction of light penetration into the sea ice/upper ocean and photosynthetically-available radiation (negative), but also reduction of effects of harmful UV radiation on ice algae given that snow is particularly effective at reducing UV transmittance (Perovich, 2001) (positive);
- Creation and maintenance of a warmer sea ice cover (due to the strong insulative properties of the snow), leading to increased permeability and vertical transport of nutrients and biological material through the ice column (positive);
- Increased ice-surface flooding (associated with increased ice temperature/permeability and snow loading), leading to more extensive surface communities and greater snow-ice formation (with the latter possibly compensating ice basal melting (Wu et al., 1999b; Maksym and Markus, 2008)) (positive, but also possibly negative given the

unavailability of surface algae to krill until the ice breaks up/is pulverised by wave action and the decreasing light levels noted above);
- Fewer nesting sites for Adélie penguins, plus the possible impact of greater frequency of snow accumulation, blizzards and snow melt on egg/chick survival (Bricher et al., 2008; Ducklow et al., 2007; Massom et al., 2006) (negative – this could also be a factor for breeding Emperor penguins);
- A delay in summer melt due to the presence of a thicker insulative, high-albedo blanket of snow, leading to a possible increased duration of sea ice in certain regions (Eicken et al., 1995; Ledley, 1991) (positive); and
- An increase in freshwater flux into the ocean (directly and via seasonal ice melt) leading to increased stratification. This would lead to changes in thermohaline convection and deep water formation (with implications for global climate, CO_2 fluxes and ocean acidification); and reductions in the upward flux of heat for basal sea ice melt (with implications that sea ice seasonality and extent would increase, e.g. Zhang, 2007). The biological implications of this scenario are complex.

Snow thickness distribution (accumulation) is dependent not only on precipitation rates but also on surface wind speed and ice surface roughness, and is therefore related to not only ice age but also its deformation history (Sturm and Massom, 2009). A corollary is that surface melt ponding, common in the central Arctic in spring–summer, may become more prevalent in the Antarctic in response to changing atmospheric conditions. This could contribute to more rapid sea ice meltback (through the ice-albedo feedback mechanism) and significantly change the properties of ice surviving the annual melt period e.g. lower ice salinity and enlarged drainage channels – as occurs in the Arctic.

A pressing need is for accurate large-scale estimates of the snow:ice thickness ratio, and its variability, in order to assess the potential distribution of surface flooding and resultant snow-ice formation (Maksym and Markus, 2008). This can only be carried out using satellites, but remains a challenge due to current underestimates of snow thickness from passive microwave data (Worby et al., 2008) and the considerable amount of validation work that is required before accurate large-scale estimates of sea ice thickness can be made from satellite altimeter data (both radar and laser).

8. Summary

There is now strong evidence that major recent changes in regional sea ice coverage are having dramatic though regionally-dependent impacts on the structure and dynamics of high-latitude marine ecosystems that are specifically adapted not only to its presence but also its seasonal rhythms and properties. Of crucial importance are substantial though contrasting changes in sea ice seasonality in the northeast and west Antarctic Peninsula (WAP) and southern Bellingshausen Sea and western Ross Sea regions (Stammerjohn et al., 2008a,b), with changes in wind direction attributed to anthropogenic climate change being a key factor. In the WAP sector, the rapid decline in sea ice has affected not only the physical environment/marine habitat but also the food web, and at multiple levels. Indeed, mounting evidence suggests that the loss of sea ice (a dominant physical change) has triggered complex cascading effects, whereby major and coincident shifts are occurring at several ecosystem levels (Siniff et al., 2008). At the base of the food web, for example, major latitudinal shifts have occurred over the last decade that reflect changing ice, ocean and atmospheric conditions and processes e.g. Montes-Hugo et al. (2009) – with crucial implications. Shifts in the periodicity of sea ice cycles and associated processes have caused spatio-temporal mismatches between phytoplankton blooms, krill development and recruitment, and krill availability to vertebrate predators (Forcada and Trathan, 2009).

The rapid local decline around Palmer Station of the Adélie penguin, a top predator which integrates the effects of variability in the physical and biological environment over large temporal and spatial scales (Fraser and Trivelpiece, 1996), and the concomitant influx of two Sub-Antarctic penguin species, underlines the dramatic nature of the change in the WAP region. Indeed, this change is unprecedented in modern times, given that chinstrap and gentoo penguins had not been locally present for at least 700 years until the first colonies were established near Palmer Station in 1976 and 1994 respectively (Emslie et al., 1998). In fact, a major additional factor adversely affecting Adélie penguin breeding success at Palmer Station is a recent increase in springtime blizzards and snow accumulation at the colony, combined with high temperatures that subsequently melt the snow at critical times in the breeding cycle (Ducklow et al., 2007). Annual changes in the populations and reproductive success of this top predator thus occur in response to two scales of processes: i) the presence/absence and characteristics of sea ice at regional scales; and ii) variability in snow accumulation at local scales (Patterson et al. 2003). Over longer ecological time scales (decades to centuries), the combined effects of these and other processes determine the extent to which habitat conditions are optimal for Adélie penguins and thus local-to-regional long-term population trends (Fraser and Trivelpiece, 1996). In addition, a direct causal relationship is apparent in this region between sea ice coverage, krill recruitment, prey availability and predator foraging ecology (Fraser and Hofmann, 2003). Years of optimal sea ice conditions that are conducive to good krill recruitment and strong year-class development are becoming increasingly infrequent (Fraser and Hofmann, 2003; Moline et al., 2008).

Different stories are emerging for Adélie penguins elsewhere in Antarctica e.g. in the Ross Sea and East Antarctica, where population stability or increase have been observed (Ainley et al., 2010). This underlines the complexity of the circumpolar situation, and suggests that the WAP Peninsular situation may be atypical to other areas. The examples of recent known ecological change from the WAP region should, however, serve as a wake-up call to the potentially serious impacts of changing sea ice coverage elsewhere around Antarctica, given the high level of vulnerability of many organisms to changing sea ice conditions. Although similar evidence of multi-level ecological/biological shifts associated with sea ice change comes from the neighbouring SW Atlantic (e.g. Murphy et al., 2008; Trathan et al., 2007) and to some extent from the SW Pacific (e.g. Ainley et al., 2005), combined biological-physical information from elsewhere around Antarctica is too fragmentary and sparse to determine whether or not long-term trends are occurring in ecosystem structure and dynamics in response to changing sea ice coverage (be it decreasing or increasing, as in the case of the western Ross Sea). Indeed, observations and understanding of how changes in the physical environment (and notably in sea ice) are linked to changes in ecosystem structure or function are largely limited or lacking. This is underpinned by a lack of fundamental knowledge of what controls the distribution of sea ice biology e.g. what processes link sea ice with the distributions of ice algae and krill, and what specific aspects of the sea ice environment are crucially important to organisms associated with it.

The importance of gaining improved understanding of current conditions and sea ice-biological linkages is emphasised by the ensemble-average GCM prediction that Antarctic sea ice will decrease in its areal extent by 24% by 2100 (Arzel et al., 2006). Unfortunately,

climate models fail to parameterise important elements of the sea ice habitat that are highly vulnerable to change yet cover relatively small areas (compared to the pack ice zone overall), including polynyas and fast ice. Dedicated high-resolution models are required for this purpose e.g. Marsland et al. (2004). Another biologically important process not currently modelled, and one that may again change in response to changing wind patterns and storminess, is wave–ice interaction. Other critical unknowns are how changes in ice sheet dynamics affect sea ice processes and habitat. For example, sea ice distribution and characteristics within the coastal area are also strongly affected by ice sheet coastal configuration, katabatic wind regimes and the presence of grounded icebergs in waters shallower than ∼350–400 m (Massom et al., 2001a). Recent examples of the rapidity of change that can occur are the disintegration of the Larsen B Ice Shelf in 2002 and the calving of the Mertz Glacier tongue in February 2010. Increased freshwater input from melting ice sheet margins and icebergs is also likely to become an increasingly important factor, with implications for ocean stratification. Changes in the latter (also driven in part by changes in sea ice distribution) are likely to have major impacts on ocean circulation and ventilation and on carbon exchange between atmosphere and ocean, with implications for ocean acidification.

Moreover, complex and at times counterintuitive impacts may result from climate change effects on elements of the Antarctic cryosphere. For example, an increase in the number of grounded icebergs calved from the ice sheet (due to an increase in glacial ice discharge) may lead to an increase in fast ice extent (depending on other factors). While conceptual only, the possible future scenarios given here indicate the complexity of possible changes and feedbacks in the atmosphere–ocean–sea ice–ice sheet system, with biotic impacts that are both negative and positive. As stated by Ducklow et al. (2007), "a major challenge involves not only documenting ecosystem responses at all levels of biotic organization (genome to planetary), but also establishing a mechanistic understanding of the linkages between climate, sea ice, biogeochemical processes and lower to upper trophic levels". To this, we could add linkages with the ice sheet and icebergs.

An important and potentially confounding factor affecting predictions of future responses/trends of Antarctic predators to climate-related sea ice (and other environmental) changes are the impacts of human disturbance (e.g. tourism), commercial fishing and whaling (in altering food webs), and also the recovery of populations of previously-harvested species (Ainley

et al., 2007; Croxall and Nicol, 2004; Siniff et al., 2008). Another complicating factor relates to the fact that ecosystems and populations are not only influenced by long-term climatic trends but also by interannual to sub-decadal variability in atmospheric forcing e.g. ENSO (Murphy et al., 2008; Trathan et al., 2007). Interactions between climate forcing and biotic and abiotic components of the Antarctic marine ecosystem, and impacts of sea ice change, are also highly complex. For example, evidence from the western Antarctic Peninsula suggests that while the declining sea ice is disastrous for some key species e.g. Adelie penguins, Antarctic krill, silverfish and possibly crabeater seals, it is beneficial for others e.g. gentoo and chinstrap penguins, elephant and fur seals and salps. Moreover, the bio-physical impacts driven by changing patterns of winds in particular and air temperature are not only complex but can also be paradoxical e.g. sea ice melt at the same time as thickening etc. This was highlighted by the case study illustrating conditions during an "extreme" event in 2001/2 in the WAP region (Massom et al., 2006). This episode strongly suggests that relatively short-term "extreme" events can have a major and often overlooked impact that is superimposed on longer-term variability/trends. A challenge remains to better understand the cumulative impact of extreme events that create abrupt shifts in time series observations, and their potential contribution to "tipping points" where the system is precariously balanced. The complexity and paradoxical nature of physical and biological impacts due to extreme events makes them difficult to predict. The case study further underlined the fact that there is far more to change in sea ice than extent alone.

The only hope of better understanding these complex relationships and links, of detecting/monitoring and predicting ecosystem response to sea ice change, of distinguishing long-term trends from natural variability/fluctuations, and of more accurately predicting future impacts, is through an integrated and highly coordinated circumpolar programme of long-term measurement and analysis of physical, biological and biogeochemical factors combined. This critical need has been recognised with the establishment of the ICED (Integrating Climate and Ecosystem Dynamics in the Southern Ocean (Murphy et al., 2008; http://www.iced.ac.uk/)) and Southern Ocean Sentinel (http://www.aad.gov.au/default.asp?casid=35088) programmes. These programmes are backed up by dedicated multi-disciplinary field programmes designed to fill in key regional gaps, state-of-the-art modelling, satellite remote sensing and standardised data collection and analysis protocols. The ongoing Palmer LTER programme is also a crucial

element, particularly given that it has uniquely acquired coordinated regional physical/biological/biogeochemical measurements on repeat cruises since 1993 (Smith et al., 2003b). The continued sustained monitoring of vertebrate colonies relative to sea ice parameters around the Antarctic coast and islands, again using state-of-the-art technology, is also crucial, given that they are effective bellwethers of change. The new Southern Ocean Observing System (http://www.noc.soton.ac.uk/CLIVAR/organization/southern/expertgroup/SOOS.htm) will play a key role in acquiring sustained integrated physical observations, in concert with Sentinel, ICED and coordinated national programmes. Another crucial factor is to better understand the complex atmospheric forcing patterns driving the change, and their linkages and teleconnections. Major sea-ice related gaps that need to be bridged include i) the under sea ice physical and biological habitat (a current "blind spot" that is being investigated using instrumented vertebrates (e.g. Charrassin et al., 2008 and autonomous underwater vehicles (Brierley and Thomas, 2002)); and ii) the large-scale measurement and monitoring the thickness distributions of Antarctic sea ice and its snow cover and the drift behaviour (dynamics) of the ice. Never have the challenges been greater, or the stakes higher.

Acknowledgements

References

Abram, N., Mulvaney, R., Wolff, E.W., Mudelsee, M., 2007. Ice core records as sea ice proxies: an evaluation from the Weddell Sea region of Antarctica. J. Geophys. Res. 112, D15101. doi:15110.11029/12006JD008139.

Ackley, S.F., Wadhams, P., Comiso, J.C., Worby, A.P., 2003. Decadal decrease of Antarctic sea ice extent inferred from whaling records revisited on the basis of historical and modern sea ice records. Polar Res. 22 (1), 19–25.

Ainley, D.G., 1983. Biomass of birds and mammals in the Ross Sea. In: Siegfried, W.R., Condy, P.R., Laws, R.M. (Eds.), Antarctic Nutrient Cycles and Food Webs. Springer-Verlag, Berlin, pp. 498–515.

Ainley, D.G., Clarke, E.D., Arrigo, K., Fraser, W.R., Kato, A., Barton, K.J., Wilson, P.R., 2005. Decadal-scale changes in the climate and biota of the biota of the Pacific sector of the Southern Ocean. Antaric Sci. 17 (2), 171–182.

Ainley, D., Ballard, G., Ackley, S., Blight, L.K., Eastman, J.T., Emslie, S.D., Lescroël, A., Olmastroni, S., Townsend, S.E., Tynan, C.T., Wilson, P., Woehler, E., 2007. Paradigm lost, or is top-down forcing no longer significant in the Antarctic marine ecosystem? Antaric Sci. 19, 283–290.

Ainley, D.G., Ballard, G., Blight, L.K., Ackley, S., Emslie, S.D., Lescroël, A., Olmastroni, S., Townsend, S.E., Tynan, C.T., Wilson, P., Woehler, E., 2009. Impacts of cetaceans on the structure of southern ocean food webs. Mar. Mamm. Sci.. doi:10.1111/j.1748-7692.2009.00337.

Ainley, D.G., Russell, J.L., Jenouvrier, S., Woehler, E., Lyver, P.O., Fraser, W.R., Kooyman, G.L., 2010. Antarctic penguin response to habitat change when Earth's troposphere reaches 2 °C above pre-industrial levels. Ecol. Monogr. 80, 49–66.

Allison, I., Barry, R.G., Goodman, B.E., 2001. Climate and Cryosphere (CLIC) Project. Science and Co-ordination Plan, Version 1. WCRP-114, WMO/TD 1053, World Climate Research Programme. World Meteorological Organization, Geneva, Switzerland.

Ancel, A., Kooyman, G.L., Ponganis, P.J., Gendner, J.-P., Lignon, J., Mestre, X., Huin, N., Thorson, P.H., Robisson, P., Le Maho, Y., 1992. Foraging behaviour of emperor penguins as a resource detector in winter and summer. Nature 360 (6402), 336–339.

Andreas, E.L., Ackley, S.F., 1981. On the difference in ablation seasons of Arctic and Antarctic sea-ice. J. Atmos. Sci. 39, 440–447.

Armand, L.K., Leventer, A., 2009. Palaeo sea ice distribution and reconstruction derived from the geological record. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 469–530.

Arrigo, K.R., van Dijken, G.L., 2003. Phytoplankton dynamics within 37 Antarctic coastal polynyas. J. Geophys. Res. 108 (C8), 3271. doi:10.1029/2002JC001739.

Arrigo, K.R., Thomas, D.N., 2004. Large scale importance of sea ice biology in the Southern Ocean. Antaric Sci. 16 (4), 471–486.

Arrigo, K.R., van Dijken, G.L., Ainley, D.G., Fahnestock, M.A., Markus, T., 2002. Ecological impact of a large Antarctic iceberg. Geophys. Res. Lett. 29 (7), 1104. doi:10.1029/2001GL014160.

Arrigo, K.R., van Dijken, G.L., Bushinsky, S., 2008. Primary production in the Southern Ocean, 1997–2006. J. Geophys. Res. 113, C08004. doi:10.1029/2007JC004551.

Arrigo, K.R., Lizotte, M.P., Mock, T., 2009. Sea ice algae. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, UK.

Arzel, O., Fichefet, T., Goosse, H., 2006. Sea ice evolutions over the 20th and 21st centuries as simulated by current AOGCMs. Ocean Model. 12, 401–415.

Atkinson, A., Siegel, V., Pakhomov, E.A., Rothery, P., 2004. Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432, 100–103.

Barber, D.G., Massom, R.A., 2007. A bi-polar assessment of modes of polynya formation. In: Smith, W.O., Barber, D.G. (Eds.), Polynyas: Windows to the World's Oceans. Elsevier, Amsterdam, pp. 1–54.

Barber-Meyer, S.M., Kooyman, G.L., Ponganis, P.J., 2008. Trends in Western Ross Sea emperor penguin chick abundances and their relationships to climate. Antarctic Sci. 20, 3–11.

Barbraud, C., Weimerskirch, H., 2001. Emperor penguins and climate change. Nature 11, 183–186.

Barbraud, C., Weimerskirch, H., 2006. Antarctic birds breed later in response to climate change. Proc. Natl. Acad. Sci. U.S.A. 103 (16), 6248–6251.

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., Boss, E.S., 2006. Climate-driven trends in contemporary ocean productivity. Nature 444, 752–755.

Bentley, C.R., Thomas, R.H., Velicogna, I., 2007. Ice sheets. In: Prestrud, P. (Ed.), Global Outlook for Ice and Snow. United Nations Environment Programme, Nairobi, pp. 99–113.

Bertolin, M.L., Schloss, I.R., 2009. Phytoplankton production after the collapse of the Larsen A Ice Shelf, Antarctica. Polar Biol. 32 (10), 1435–1446.

Bindoff, N.L., Rintoul, S.R., Massom, R., 2000. Bottom water formation and polynyas in Adélie Land, Antarctica. Pap. Proc. Roy. Soc. Tasm. 133 (3), 51–56.

Bluhm, B.A., Gradinger, R.R., Schnack-Schiel, S.B., 2009. Sea ice meio- and macrofauna. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford.

Bracegirdle, T.J., Connolley, W.M., Turner, J., 2008. Antarctic climate change over the 21st century. J. Geophys. Res. 113, D03103. doi:10.1029/2007JD008933.

Bricher, P.K., Lucieer, A., Woehler, E.J., 2008. Population trends of Adélie penguin (Pygoscelis adeliae) breeding colonies: a spatial analysis of the effects of snow accumulation and human activities. Polar Biol. 31, 1397–1407.

Brierley, A.S., Thomas, D.N., 2002. Ecology of Southern Ocean pack ice. Adv. Mar. Ecol. 2002 (43), 171–276.

Brierley, A.S., Fernandes, P.G., Brandon, M.A., Armstrong, N.W., McPhail, S.D., Steveson, P., Pebody, M., Perrett, J., Squires, M., Bone, D.G., Griffiths, G., 2002. Antarctic krill under sea ice: elevated abundance in a narrow band just south of ice edge. Science 295, 1890–1892.

Burns, J.M., Kooyman, G.L., 2001. Habitat use by Weddell seals and Emperor penguins foraging in the Ross Sea, Antarctica. Am. Zool. 41 (1), 90–98.

Caron, D.A., Gast, R.J., 2009. Heterotrophic protists associated with sea ice. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford.

Charrassin, J.-B., Hindell, M., Rintoul, S.R., Roquet, F., Sokolov, S., Biuw, M., Costa, D., Boehme, L., Lovell, P., Coleman, R., Timmermann, R., Meijers, A., Meredith, M., Park, Y.-H., Bailleul, F., Goebel, M., Tremblay, Y., Bost, C.-A., McMahon, C.R., Field, I.C., Fedak, M.A., Guinet, C., 2008. Southern Ocean frontal structure and sea-ice formation rates revealed by elephant seals. Proc. Natl. Acad. Sci. U.S.A. 105 (33), 11634–11639.

Clarke, A., Murphy, E.J., Meredith, M.P., King, J.C., Peck, L.S., Barnes, D.K.A., Smith, R.C., 2007. Climate change and the marine ecosystem of the western Antarctic Peninsula. Phil. Trans. Roy. Soc. Lond. B Biol. Sci. 362, 149–166.

Clarke, A., Brierley, A.S., Harris, C.M., Lubin, D., Smith, R.C., 2008. Polar and ice-edge marine systems. In: Polunin, N.V.C. (Ed.), Aquatic Ecosystems: Trends and Global Prospects. Cambridge University Press, Cambridge, pp. 319–333.

Comiso, J., 1999. Bootstrap Sea Ice Concentrations from NIMBUS-7 SMMR and DMSP SSM/I. National Snow and Ice Data Centerm Digital Media, Boulder, Colorado, USA. Updated 2008.

Comiso, J.C., 2003. Large-scale characteristics and variability of the global sea ice cover. In: Thomas, D., Dieckmann, G. (Eds.), Sea Ice: An Introduction to Its Physics, Chemistry, Biology and Geology. Blackwell Scientific Publishing, Oxford, pp. 112–142.

Comiso, J.C., Nishio, F., 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. J. Geophys. Res. 113, C02S07. doi:10.1029/2007JC004257.

Convey, P., 2007. Antarctic climate change and its influences on terrestrial ecosystems. In: Bergstrom, D.M., Convey, P., Huiskes, A.H.L. (Eds.), Trends in Antarctic Terrestrial and Limnetic Ecosystems. Springer, pp. 253–272.

Croxall, J.P., Nicol, S., 2004. Management of Southern Ocean resources: global forces and future sustainability. Antarctic Sci. 16, 569–584.

Croxall, J.P., Trathan, P.N., Murphy, E.J., 2002. Environmental change and Antarctic seabird populations. Science 297, 1510–1514.

Curran, M.A.J., van Ommen, T.D., Morgan, V.I., Phillips, K.L., Palmer, A.S., 2003. Ice core evidence for Antarctic sea ice decline since the 1950s. Science 302, 1203–1206.

de la Mare, W.K., 1997. Abrupt mid-twentieth century decline in Antarctic sea ice extent from whaling records. Nature 389, 57–60.

de la Mare, W.K., 2008. Changes in Antarctic sea ice extent from direct historical observations and whaling records. Clim. Change. doi:10.1007/s10584-008-9473-2.

Delille, B., Jourdain, B., Borges, A.V., Tison, J.-L., Delille, D., 2007. Biogas (CO_2, O_2, dimethylsulfide) dynamics in spring Antarctic fast ice. Limnol. Oceanogr. 52 (4), 1367–1379.

Deming, J.W., 2009. Sea ice bacteria and viruses. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford.

Dieckmann, G.A., Hellmer, H., 2009. The importance of sea ice: an overview. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 1–22.

Dieckmann, G.S., Nehrke, G., Papadimitriou, S., Göttlicher, J., Steininger, R., Kennedy, H., Wolf-Gladrow, D., Thomas, D.N., 2008. Calcium carbonate as ikaite crystals in Antarctic sea ice. Geophys. Res. Lett. 35, L08501. doi:10.1029/2008GL033540.

Dierssen, H.M., Smith, R.C., Vernet, M., 2002. Glacial meltwater dynamics in coastal waters West of the Antarctic Peninsula. Proc. Natl. Acad. Sci. U.S.A. 99, 1790–1795.

Doney, S.C., Tilbrook, B., Roy, S., Metzl, N., Le Quéré, C., Hood, M., Feely, R.A., Bakker, D., 2009a. Surface ocean CO_2 variability and vulnerability. Deep Sea Res. II 56, 504–511.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009b. Ocean acidification: the other CO_2 problem. Ann. Rev. Mar. Sci. 1, 169–192. doi:10.1146/annurev.marine.010908.163834.

Dubischar, C.D., Pakhomov, E.A., Bathmann, U.V., 2006. The tunicate *Salpa thompsoni* ecology in the Southern Ocean II. Proximate and elemental composition. Mar. Biol. 149, 625–632.

Ducklow, H.W., Baker, K., Martinson, D.G., Quetin, L.B., Ross, R.M., Smith, R.C., Stammerjohn, S.E., Vernet, M., Fraser, W.R., 2007. Marine pelagic ecosystems: the West Antarctic Peninsula. Phil. Trans. Roy. Soc. Lond. B Biol. Sci. B362, 67–94.

Eicken, H., 1992. The role of sea ice in structuring Antarctic ecosystems. Polar Biol. 12, 3–13.

Eicken, H., Fischer, H., Lemke, P., 1995. Effects of the snow cover on Antarctic sea ice and potential modulation of its response to climate change. Ann. Glaciol. 21, 369–376.

Emmerson, L., Southwell, C., 2008. Sea ice cover and its influence on Adélie penguin reproductive performance. Ecology 89 (8), 2096–2102.

Emslie, S.D., Fraser, W., Smith, R.C., Walker, W., 1998. Abandoned penguin colonies and environmental change in the Palmer Station area, Anvers Island, Antarctic Peninsula. Antartic Sci. 10, 257–268.

Emslie, S.D., Patterson, W.P., 2007. Abrupt recent shift in δ13C and δ15N values in Adélie penguin eggshell in Antarctica. Proc. Natl. Acad. Sci. U.S.A. 104 (28), 11666–11669.

Fabry, V.J., McClintock, J.B., Mathis, J.T., Grebmeier, J.C., 2009. Ocean acidification at high latitudes: the bellwether. Oceanography 22 (4), 160–171.

Fichefet, T., Arzel, O., Goosse, H., 2008. On the ability of current atmosphere-ocean general circulation models to predict the evolution of sea ice. WCRP-SCAR CliC Ice. Clim. News 10 (1), 5–6.

Fogt, R.L., Bromwich, D.H., 2006. Decadal variability of the ENSO teleconnection to the high latitude South Pacific governed by coupling with the southern annular mode. J. Clim. 19, 979–997.

Forcada, J., Trathan, P.N., 2009. Penguin responses to climate change in the Southern Ocean. Global Change Biol. 15, 1618–1630.

Forcada, J., Trathan, P.N., Reid, K., Murphy, E.J., Croxall, J.P., 2006. Contrasting population changes in sympatric penguin species with climate warming. Global Change Biol. 12, 411–423. doi:10.1111/j.1365-2486.2006.01108.x.

Foster, A., Curran, M.A.J., van Ommen, T.D., Morgan, V., 2006. Covariation of sea ice and methane sulphonic acid in Wilhelm II Land, Antarctica. Ann. Glaciol. 44, 429–432.

Fox, C., Haskell, T.G., 2001. Ocean wave speed in the Antarctic marginal ice zone. Ann. Glaciol. 33, 350–354.

Fraser, A.D., Massom, R.A., Michael, K.J., 2009. A method for compositing polar MODIS images to remove cloud cover for landfast sea-ice detection. IEEE Trans. Geosc. Rem. Sens. 47 (9), 3272–3282.

Fraser, A.D., Massom, R.A., Michael, K.J. High-resolution East Antarctic landfast sea-ice maps from cloud-free MODIS satellite composite imagery. Rem. Sens. Environ., in preparation.

Fraser, W.R., Hofmann, E.E., 2003. A predator's perspective on causal links between climate change, physical forcing and ecosystem response. Mar. Ecol. Progr. Ser. 265, 1–15.

Fraser, W.R., Trivelpiece, W.Z., 1996. In: Ross, R.M., Hofmann, E., Quetin, L.B. (Eds.), Factors Controlling the Distribution of Seabirds: Winter–Summer Heterogeneity in the Distribution of Adélie Penguin Populations. Antarctic Research Series 70. Foundations for Ecological Research West of the Antarctic Peninsula, AGU, Washington DC, pp. 257–272.

Fraser, W.R., Patterson, D.L., 1997. Human disturbance and long-term changes in Adelie penguin populations: a natural experiment at Palmer Station, Antarctic Peninsula. In: Battaglia, B., Valencia, J., Walton, D.W.H. (Eds.), Antarctic: Communities: Species, Structure and Survival. Cambridge University Press, Cambridge, pp. 445–452.

Frazer, T.K., Quetin, L.B., Ross, R.M., 1997. Abundance and distribution of larval krill, *Euphausia superba*, associated with annual sea ice in winter. In: Battaglia, B., Valencia, J., Walton, D.W.H. (Eds.), Antarctic: Communities: Species, Structure and Survival. Cambridge University Press, Cambridge, pp. 107–111.

Fritsen, C.H., Kremer, J.N., Ackley, S.F., Sullivan, C.W., 1998. Flood-freeze cycles and algal dynamics in Antarctic pack ice. In: Lizotte, M.L., Arrigo, K.R. (Eds.), Antarctic Sea Ice: Biological Processes. Antarctic Research Series 73. American Geophysical Union, Washigton DC, pp. 1–21.

Fyfe, J.C., Saenko, O.A., Zickfeld, K., Eby, M., Weaver, A.J., 2007. The role of poleward – intensifying winds on Southern Ocean warming. J. Clim. 20 (21), 5391–5400.

Garibotti, I.A., Vernet, M., Kozlowski, W.A., Ferrario, M.E., 2003. Composition and biomass of phytoplankton assemblages in coastal Antarctic waters: a comparison of chemotaxonomic and microscopic analyses. Mar. Ecol. Progr. Ser. 247, 27–42.

Garrison, D.L., Ackley, S.F., Buck, K.R., 1983. A physical mechanism for establishing algal populations in frazil ice. Nature 306, 363–365.

Giles, A.B., Massom, R.A., Lytle, V.I., 2008a. Fast ice distribution in East Antarctica during 1997 and 1999 determined using Radarsat data. J. Geophys. Res. (Oceans) 113, C02S14. doi:10.1029/2007JC004139.

Giles, K.A., Laxon, S.W., Worby, A.P., 2008b. Antarctic sea ice elevation from satellite radar altimetry. Geophys. Res. Lett. 35, L03503. doi:10.1029/2007GL031572.

Gillet, N.P., Thompson, D.W.J., 2003. Simulation of recent Southern Hemisphere climate change. Science 302, 273–275.

Gloersen, P., Campbell, W.J., Cavalieri, D.J., Comiso, J.C., Parkinson, C.L., Zwally, H.J., 1992. Arctic and Antarctic Sea Ice, 1978-1987: Satellite Passive-Microwave Observations and Analysis. NASA Special Publication SP-511. NASA, Washington DC, 290 pp.

Golden, K.M., Ackley, S.F., Lytle, V.I., 1998. The percolation phase transition in sea ice. Science 282, 2238–2241.

Goodison, B.E., Brown, R.D., Crane, R.G., 1999. Cryospheric systems. In: King, M.D. (Ed.), EOS Science Plan: The State of Science in the EOS Program. NASA NP-1998-12-069-GSFC. NASA Goddard Space Flight Center, Greenbelt, MD, USA, pp. 261–307.

Goosse, H., Renssen, H., 2005. A simulated reduction in Antarctic sea-ice area since 1750: implications of the long memory of the ocean. Int. J. Climatol. 25, 569–579.

Gruber, N., Gloor, M., Fletcher, S.E.M., Doney, S.C., Dutkiewicz, S., Follows, M.J., Gerber, M., Jacobson, A.R., Joos, F., Lindsay, K., Menemenlis, D., Mouchet, A., Muller, S.A., Sarmiento, J.L., Takahashi, T., 2009. Oceanic sources, sinks, and transport of atmospheric CO_2. Global Biogeochem. Cycles 23, GB1005. doi:10.1029/2008GB003349.

Gutt, J., Starmans, A., 2001. Quantification of iceberg impact and benthic recolonisation patterns in the Weddell Sea (Antarctica). Polar Biol. 24, 615–619.

Haas, C., 2009. Dynamics versus thermodynamics: the sea ice thickness distribution. In: Thomas, D.G., Dieckmann, G.S.

(Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 114−150.

Hadley, G.L., Rotella, J.J., Garrott, R.A., 2007. Influence of maternal characteristics and oceanographic conditions on survival and recruitment probabilities of Weddell seals. Oikos 116, 601−613.

Harangozo, S.A., 2006. Atmospheric circulation impacts on winter maximum sea ice extent in the west Antarctic Peninsula region (1979−2001). Geophys. Res. Lett. 33, L02502. doi:10.1029/2005GL024978.

Heil, P., 2006. Atmospheric conditions and fast ice at Davis, East Antarctica: a case study. J. Geophys. Res. 111, C05009. doi:10.1029/2005JC002904.

Heil, P., Allison, I., 1999. The pattern and variability of Antarctic sea-ice drift in the Indian Ocean and western Pacific sectors. J. Geophys. Res. 104 (C7), 15789−15802.

Hibler III, W.D., 1986. Ice dynamics. In: Untersteiner, N. (Ed.), The Geophysics of Sea Ice. Plenum Press, New York, pp. 577−640.

Hinke, J.T., Salwicka, K., Trivelpiece, S.G., Watters, G.M., Trivelpiece, W.Z., 2007. Divergent responses of *Pygoscelis* penguins reveal a common environmental driver. Oecologia 153, 845−855.

Horner, R., Ackley, S.F., Dieckmann, G.S., Gulliksen, B., Hoshai, T., Legendre, L., Melnikov, I.A., Reeburgh, W.S., Spindler, M., Sullivan, C.W., 1992. Ecology of sea ice biota. 1. Habitat, terminology and methodology. Polar Biol. 12, 417−427.

IPCC, 2007. Summary for Policymakers. In: Solomon, S., Qin, D.M., Manning, Z., Chen, M., Marquis, K.B., Avery, T., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jacobs, S., 2006. Observations of change in the Southern Ocean. Phil. Trans. Roy. Soc. A 364, 1657−1681.

Jacobs, S.S., Giulivi, C.F., Mele, P.A., 2002. Freshening of the Ross Sea during the late 20th century. Science 297, 386−389.

Jenouvrier, S., Weimerskirch, H., Barbraud, C., Park, Y.-H., Cazelles, B., 2005a. Evidence of a shift in the cyclicity of Antarctic seabird dynamics linked to climate. Proc. Roy. Soc. B 272, 887−895.

Jenouvrier, S., Barbraud, C., Weimerskirch, H., 2005b. Long-term contrasted responses to climate of two Antarctic seabird species. Ecology 86 (11), 2889−2903.

Jenouvrier, S., Caswell, H., Barbraud, C., Holland, M., Stroeve, J., Weimerskirch, H., 2009. Demographic models and IPCC climate projections predict the decline of an emperor penguin population. Proc. Natl. Acad. Sci. U.S.A.. doi:10.1073/pnas. 0806638106.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteor. Soc. 77, 437−471.

Kern, S., 2009. Wintertime Antarctic coastal polynya area: 1992−2008. Geophys. Res. Lett. 36, L14501. doi:10.1029/2009GL038062.

Kirkwood, R., Robertson, G., 1997. Seasonal change in the foraging ecology of emperor penguins on the Mawson Coast, Antarctica. Mar. Ecol. Progr. Ser. 156, 205−223.

Klinck, J.M., Hofmann, E.E., Beardsley, R.C., Salihoglu, B., Howard, S., 2004. Water-mass properties and circulation on the west Antarctic Peninsula continental shelf in austral fall and winter 2001. Deep Sea Res. II 51 (17−19), 1925−1946.

Kooyman, G.L., 1993. Breeding habitats of Emperor penguins in the western Ross Sea. Antartic Sci. 5, 143−148.

Kooyman, G.L., Ainley, D.G., Ballard, G., Ponganis, P.J., 2007. Effects of giant icebergs on two emperor penguin colonies in the Ross Sea, Antarctica. Antartic Sci. 19, 31−38.

Kushner, P.J., Held, I.M., Delworth, T.L., 2001. Southern Hemisphere atmospheric circulation response to global warming. J. Clim. 14, 2238−2249.

Kwok, R., Comiso, J.C., 2002. Southern Ocean climate and sea ice anomalies associated with the Southern Oscillation. J. Clim. 15, 487−501.

Langhorne, P., Squire, V.A., Fox, C., Haskell, T.G., 2001. Lifetime estimation for a land-fast ice sheet subjected to ocean swell. Ann. Glaciol. 33, 333−338.

Lannuzel, D., Schoemann, V., de Jong, J., Tison, J.-L., Chou, L., 2007. Distribution and biogeochemical behaviour of iron in East Antarctic sea ice. Mar. Chem. 106 (1−2), 18−32.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E.T., Conway, T.J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillet, N., Heimann, M., 2007. Saturation of the Southern Ocean CO_2 sink due to recent climate change. Science 316 (5832), 1735−1738. doi:10.1126/science. 1136188.

Ledley, T.S., 1991. Snow on sea ice: competing effects in shaping climate. J. Geophys. Res. 96, 17195−17208.

Lefebvre, W., Goosse, H., 2008. Analysis of the projected regional sea ice changes in the Southern Ocean during the twenty-first century. Clim. Dynam. 30 (1), 59−76.

Lefebvre, W., Goosse, H., Timmermann, R., Fichefet, T., 2004. Influence of the southern annular mode on the sea-ice−ocean system. J. Geophys. Res. 109, C090005. doi:10.1029/2004JC002403.

Leppäranta, M., 2005. The Drift of Sea Ice. Springer Praxis Books, 272 pp.

Liu, J., Curry, J.A., Martinson, D.G., 2004. Interpretation of recent Antarctic sea ice variability. Geophys. Res. Lett. 31, L02205. doi:10.1029/2003GL018732.

Lizotte, M.P., 2003. Microbiology of sea ice. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice − an Introduction to Its Physics, Chemistry, Biology and Geology. Blackwell Science, Oxford, UK, pp. 184−210.

Loeb, V., Siegel, V., Holm-Hansen, O., 1997. Effects of sea-ice extent and salp or krill dominance on the Antarctic food web. Nature 387, 897−900.

Lovenduski, N.S., Gruber, N., Doney, S.C., Lima, I.D., 2007. Enhanced CO_2 outgassing in the Southern Ocean from a positive phase of the southern annular mode. Global Biogeochem. Cycles 21 (2), GB2026. doi:10.1029/2006GB002900.

Lovenduski, N.S., Gruber, N., Doney, S.C., 2008. Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink. Global Biogeochem. Cycles 22 (3), GB3016. doi:10.1029/2007GB003139.

Lubin, D., Massom, R.A., 2006. Polar Remote Sensing. In: Atmosphere and Oceans, vol. I. Praxis/Springer-Verlag, Chichester/Berlin, 756 pp.

Lubin, D., Wittenmyer, R.A., Bromwich, D.H., Marshall, G.J., 2008. Antarctic Peninsula mesoscale cyclone variability and climatic impacts influenced by the SAM. Geophys. Res. Lett. 35, L02808. doi:10.1029/2007GL032170.

Lytle, V.I., Massom, R., Bindoff, N., Worby, A., Allison, I., 2000. Wintertime heat flux to the underside of East Antarctic pack ice. J. Geophys. Res. 105 (C12), 28759−28769.

Maksym, T., Markus, T., 2008. Antarctic sea ice thickness and snow-to-ice conversion from atmospheric reanalysis and passive microwave snow depth. J. Geophys. Res. 113, C02S12. doi:10.1029/2006JC004085.

Marshall, G.J., Stott, P.A., Turner, J., Connolley, W.M., King, J.C., Lachlan-Cope, T.A., 2004. Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. Geophys. Res. Lett. 31, L14205. doi:10.1029/2004GL019952.

Marschall, H.-P., 1988. The overwintering strategy of Antarctic krill under the pack ice of the Weddell Sea. Polar Biol. 2, 245−250.

Marsland, S.J., Bindoff, N.L., Williams, G.D., Budd, W.F., 2004. Modelling water mass formation in the Mertz Glacier Polynya and Adélie Depression, East Antarctica. J. Geophys. Res. 109, C11003. doi:10.1029/2004JC002441.

Martin, S., Drucker, R., Kwok, R., 2007. The areas and ice production of the western and central Ross Sea polynyas, 1991−2002 and their relation to the B-15 and C-19 iceberg events of 2000 and 2002. J. Mar. Syst. 68. doi:10.1016/j.jmarsys.2006.11.008.

Martinson, D.G., Stammerjohn, S.E., Smith, R.C., Iannuzzi, R.A., 2008. Palmer, Antarctica, Long-Term Ecological Research program first 12 years: physical oceanography, spatio-temporal variability. Deep Sea Res. II 55. doi:10.1016/j.dsr2.2008.04.038.

Massom, R.A., Drinkwater, M.R., Haas, C., 1997. Winter snow cover on sea ice in the Weddell Sea. J. Geophys. Res. 102 (C1), 1101−1117.

Massom, R.A., Harris, P.T., Michael, K.J., Potter, M.J., 1998. The distribution and formative processes of latent heat polynyas in East Antarctica. Ann. Glaciol. 27, 420−426.

Massom, R.A., Comiso, J.C., Worby, A.P., Lytle, V.I., Stock, L., 1999. Regional classes of sea ice cover in the East Antarctic pack from satellite and in situ data during the winter time period. Rem. Sens. Environ. 68 (C1), 61−76.

Massom, R.A., Hill, K.L., Lytle, V.I., Worby, A.P., Paget, M.J., Allison, I., 2001a. Effects of regional fast-ice and iceberg distributions on the behaviour of the Mertz Glacier polynya, East Antarctica. Ann. Glaciol. 33, 391−398.

Massom, R.A., Eicken, H., Haas, C., Jeffries, M.O., Drinkwater, M.R., Sturm, M., Worby, A.P., Wu, X., Lytle, V.I., Ushio, S., Morris, K., Reid, P.A., Warren, S., Allison, I., 2001b. Snow on Antarctic sea ice. Rev. Geophys. 39 (3), 413−445.

Massom, R.A., Stammerjohn, S.E., Smith, R.C., Pook, M.J., Iannuzzi, R.A., Adams, N., Martinson, D.G., Vernet, M., Fraser, W.R., Quetin, L.B., Ross, R.M., Massom, Y., Krouse, H.R., 2006. Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/2, and its profound impact on sea ice and biota. J. Clim. 19, 3544−3571.

Massom, R., Stammerjohn, S., Lefebvre, W., Harangozo, S., Adams, N., Scambos, T., Pook, M., Fowler, C., 2008. West Antarctic Peninsula sea ice in 2005: extreme ice compaction and ice edge retreat due to strong anomaly with respect to climate. J. Geophys. Res. 113, C02S20. doi:10.1029/2007JC004239.

Massom, R.A., Hill, K., Barbraud, C., Adams, N., Ancel, A., Emmerson, L., Pook, M., 2009. Fast ice distribution in Adélie Land, East Antarctica: interannual variability and implications for emperor penguins (*Aptenodytes forsteri*). Mar. Ecol. Progr. Ser. 374, 243−257.

Massom, R.A., O'Farrell, S., Adams, N., Armand, L., Meiners, K., Arrigo, K., Curran, M., Heil, P., Pasquer, B. Observing and modelling Antarctic sea ice habitats. Progr. Oceanogr., in preparation.

Mayewski, P.A., et al., 2009. State of the Antarctic and Southern Ocean climate system. Rev. Geophys. 47, RG1003. doi:10.1029/2007RG000231.

Maykut, G.A., 1986. The surface heat and mass balance. In: Untersteiner, N. (Ed.), The Geophysics of Sea Ice, Series B: Physics, vol. 146. Plenum Press, New York, pp. 395−463.

Maykut, G.A., Untersteiner, N., 1971. Some results from a time-dependent thermodynamic model of sea ice. J. Geophys. Res. 76 (6), 1550−1575.

McClintock, J., Ducklow, H., Fraser, W., 2008. Ecological impacts of climate change on the Antarctic Peninsula. Am. Sci. 96, 302−310.

McMahon, C., Hindell, M., Dorr, A., Massom, R.A., 2002. Winter distribution and abundance of Crabeater seals off George V Land, East Antarctica. Antarctic Sci. 14 (2), 128−133.

McMinn, A., Ashworth, C., Ryan, K.G., 2000. In situ primary production of an Antarctic fast ice bottom algal community. Aquat. Microb. Ecol. 21, 177−185.

McNeil, B.I., Matear, R.J., 2008. Southern Ocean acidification: a tipping point at 450-ppm atmospheric CO_2. Proc. Natl. Acad. Sci. U.S.A. 105 (48), 18860−18864.

Meredith, M.P., King, J.C., 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophys. Res. Lett. 32, L19604. doi:10.1029/2005GL024042.

Moline, M.A., Claustre, H., Frazer, T.K., Schofield, O., Vernet, M., 2004. Alteration of the food web along the Antarctic Peninsula in response to a regional warming trend. Global Change Biol. 10 (12), 1973−1980.

Moline, M.A., Karnovsky, N.J., Brown, Z., Divoky, G.J., Frazer, T.R., Jacoby, C.A., Torres, J.J., Fraser, W.R., 2008. High latitude changes in ice dynamics and their impact on polar marine ecosystems. Ann. N.Y. Acad. Sci. 1134, 267−319.

Monaghan, A.J., et al., 2006. Insignificant change in Antarctic snowfall since the International Geophysical Year. Science 313 (5788), 827−831.

Montes-Hugo, M., Doney, S.C., Ducklow, H.W., Fraser, W., Martinson, D., Stammerjohn, S.E., Schofield, O., 2009. Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula. Science 323 (5920), 1470−1473.

Moy, A.D., Howard, W.R., Bray, S.G., Trull, T.W., 2009. Reduced calcification in modern Southern Ocean planktonic foraminifera. Nat. Geosci. 2, 276−280.

Murphy, E.J., Clarke, A., Symon, C., Priddle, J.J., 1995. Temporal variation in Antarctic sea-ice: analysis of a long term fast-ice record from the South Orkney Islands. Deep Sea Res. I 42 (7), 1045−1062.

Murphy, E.J., Morris, D.J., Watkins, J.L., Priddle, J., 1988. Scales of interaction between Antarctic krill and the environment. In: Sahrhage, D. (Ed.), Antarctic Ocean and Resources Variability. Springer, Berlin, pp. 120−130.

Murphy, E.J., Trathan, P.N., Watkins, J.L., et al., 2007. Climatically driven fluctuations in Southern Ocean ecosystems. Proc. Roy. Soc. B 274, 3057−3067.

Murphy, E.J., Cavanagh, R.D., Johnston, N.M., Reid, K., Hofmann, E.E. (Eds.), 2008. Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED): A Circumpolar Ecosystem Programme. Science Plan and Implementation Strategy, p. 68. GLOBEC Report No. 26.

Nicol, S., 2006. Krill, currents, and sea ice: *Euphausia superba* and its changing environment. Bioscience 56, 111—120.

Nicol, S., Pauly, T., Bindoff, N.L., Wright, S., Thiele, D., Hosie, G.W., Strutton, P.G., Woehler, E., 2000. Ocean circulation off East Antarctica affects ecosystem structure and sea—ice extent. Nature 406, 504—507.

Nicol, S., Worby, A., Leaper, R., 2008. Changes in the Antarctic sea-ice ecosystem: potential effect on krill and baleen whales. Mar. Freshwat. Res. 59, 361—382.

Olivier, F., van Franeker, J.A., Creuwels, J., Woehler, E.J., 2004. Breeding performance variability of snow petrels *Pagodroma nivea* at Casey (East Antarctica) in relation to large scale environmental factors. Polar Biol. 28, 687—699.

Parkinson, C.L., 1990. Search for Little Ice Age in Southern Ocean sea-ice records. Ann. Glaciol. 14, 221—225.

Parkinson, C.L., 2002. Trends in the length of the Southern Ocean sea ice season, 1979—1999. Ann. Glaciol. 34, 435—440.

Parkinson, C.L., Vinnikov, K.Y., Cavalieri, D.J., 2006. Evaluation of the simulation of the annual cycle of Arctic and Antarctic sea ice coverages by 11 major global climate models. J. Geophys. Res. 111, C07012. doi:10.1029/2005JC003408.

Patterson, D.L., Easter-Pilcher, A., Fraser, W.R., 2003. The effects of human activity and environmental variability on long-term changes in Adélie penguin populations at Palmer Station, Antarctica. In: Huiskes, A.H.L. (Ed.), Antarctic Biology in a Global Context. Scientific Committee for Antarctic Research (SCAR), Eighth Biological Symposium. Backhuys Publishers, pp. 301—307.

Peck, L.S., Barnes, D.K.A., Cook, A.J., Fleming, A.H., Clarke, A., 2009. Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. Global Change Biol.. doi:10.1111/j.1365-2486.2009.02071.x.

Perovich, D.K., 2001. UV radiation and optical properties of sea ice and snow. In: Hessen, D. (Ed.), UV-Radiation and Arctic Ecosystems. Springer-Verlag, Heidelberg, pp. 73—89.

Perovich, D.K., Richter-Menge, J.A., 2009. Loss of sea ice in the Arctic. Ann. Rev. Mar. Sci. 1, 417—441.

Petrich, C., Eicken, H., 2009. Growth, structure and properties of sea ice. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 23—77.

Proffitt, K.M., Garrott, R.A., Rotella, J.J., Siniff, D.B., Testa, J.W., 2007. Exploring linkages between abiotic oceanographic processes and a top-trophic predator in an Antarctic ecosystem. Ecosystems 10, 119—126.

Quetin, L.B., Ross, R.M., 2003. Episodic recruitment in Antarctic krill, *Euphausia superba* in the Palmer LTER study region. Mar. Ecol. Progr. Ser. 259, 185—200.

Quetin, L.B., Ross, R.M., Fritsen, C.H., Vernet, M., 2007. Ecological responses of Antarctic krill to environmental variability: can we predict the future? Antartic Sci. 19, 1—14.

Quetin, L.B., Ross, R.M., 2009. Life under Antarctic pack ice: a krill perspective. In: Krupnik, I., Lang, M.A., Miller, S.E. (Eds.), Smithsonian at the Poles: Contributions to International Polar Year Science. Smithsonian Inst., Washington DC, pp. 285—298.

Raphael, M.N., 2007. The influence of atmospheric zonal wave three on Antarctic sea ice variability. J. Geophys. Res. 112 (D12), D12112.

Raymond, B., Meiners, K., Fowler, C., Pasquer, B., Williams, G., Nicol, S., 2009. Cumulative solar irradiance and potential large-scale sea ice algae distribution off East Antarctica (30°E—150°E). Polar Biol. 32 (3), 443—452.

Rhodes, R.N., Bertler, A.N., Baker, J.A., Sneed, S.B., Oerter, H., Arrigo, K.R., 2009. Sea ice variability and primary productivity in the Ross Sea, Antarctica, from methylsulphonate snow record. Geophys. Res. Lett. 36, L10704. doi:10.1029/2009GL037311.

Ribic, C.A., Chapman, E., Fraser, W.R., Lawson, G.L., Wiebe, P.H., 2008. Top predators in relation to bathymetry, ice, and krill during austral winter in Marguerite Bay, Antarctica. Deep Sea Res. II 55, 485—499.

Rignot, E., Bamber, J.L., van den Broeke, M.R., Davis, C., Li, Y., van den Berg, W.J., van Meijgaard, E., 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nat. Geosci. 1, 106—110.

Rintoul, S.R., 1998. On the origin and influence of Adélie Land Bottom Water. In: Jacobs, S., Weiss, R. (Eds.), Ocean, Ice and the Atmosphere: Interactions at the Antarctic Continental Margin. Antarctic Research Series 75. American Geophysical Union, Washington, D.C, pp. 151—171.

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

Ross, R.M., Quetin, L.B., Newberger, T., Oakes, S.A., 2004. Growth and behavior of larval krill (*Euphausia superba*) under the ice in late winter 2001 west of the Antarctic Peninsula. Deep Sea Res. II 51, 2169—2184.

Ross, R.M., Quetin, L.B., Martinson, D.G., Iannuzzi, R., Stammerjohn, S.E., Smith, R.C., 2008. Palmer LTER: patterns of distribution of 5 dominant zooplankton species in the epipelagic zone west of the Antarctic Peninsula, 1993—2004. Deep Sea Res. II 55. doi:10.1016/j.dsr2.2008.04.037.

Satoh, H., Watanabe, K., 1988. Primary productivity in the fast ice area near Syowa Station, Antarctica, during spring and summer 1983/84. J. Oceanogr. Soc. Jpn 44, 287—292.

Scambos, T.A., Fricker, H.A., Liu, C.-C., Bohlander, J., Fastook, J., Sargent, A., Massom, R., 2009. Ice shelf disintegration by plate bending and hydro-fracture: satellite observations and model results of the 2008 Wilkins Ice Shelf break-ups. Earth Planet Sci. Lett. 280, 51—60.

Scambos, T.A., Hulbe, C., Fahnestock, M., 2003. Climate-induced ice shelf disintegration in the Antarctic Peninsula. In: Domack, E., Leventer, A., Burnett, A., Bindschadler, R., Convey, P., Kirby, M. (Eds.), Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspective. American Geophysical Union, Washington, DC, pp. 79—92.

Shindell, D.T., Schmidt, G.A., 2004. Southern Hemisphere climate response to ozone changes and greenhouse gas increases. Geophys. Res. Lett. 31. doi:10.1029/2004GL020724.

Simmonds, I., Jacka, T.H., 1995. Relationships between the inter-annual variability of Antarctic sea ice and the Southern Oscillation. J. Clim. 8, 637—647.

Simmonds, M.P., Eliot, W.J., 2009. Climate change and cetaceans: concerns and recent developments. J. Marine Biol. Assoc. UK 89 (1), 203—210.

Siniff, D.B., Garrott, R.A., Rotella, J.J., Fraser, W.R., Ainley, D.G., 2008. Projecting the effects of environmental change on Antarctic seals. Antartic Sci. 20 (5), 425—435.

Smale, D.A., Barnes, D.K.A., Fraser, K.P.P., 2007. The influence of depth, site exposure and season on the intensity of iceberg scouring in nearshore Antarctic waters. Polar Biol. 30, 769—779.

Smetacek, V., Scharek, R., Nöthig, E.M., 1990. Seasonal and regional variation in the pelagial and its relationship to the life history cycle of krill. In: Kerry, K.R., Hempel, G. (Eds.), Antarctic Ecosystems: Ecological Change and Conservation. Springer Verlag, Berlin, pp. 103—114.

Smetacek, V., Nicol, S., 2005. Polar ocean ecosystems in a changing world. Nature 437, 362–368.

Smith, R.C., Fraser, W.R., Stammerjohn, S.E., 2003a. Climate variability and ecological response of the marine ecosystem in the western Antarctic Peninsula (WAP) region. In: Greenland, D., Goodin, D.G., Smith, R.C. (Eds.), Climate Variability and Ecosystem Response at Long-Term Ecological Research (LTER) Sites. Oxford University Press, New York, pp. 158–173.

Smith, R.C., Fraser, W.R., Stammerjohn, S.E., Vernet, M., 2003b. Palmer Long-Term Ecological Research on the Antarctic marine ecosystem. In: Domack, E., Leventer, A., Burnett, A., Bindschadler, R., Convey, P., Kirby, M. (Eds.), Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspective. American Geophysical Union, Washington, DC, pp. 131–144.

Smith Jr., W.O., Comiso, J.C., 2008. Influence of sea ice on primary production in the Southern Ocean: a satellite perspective. J. Geophys. Res. 113, C05S93. doi:10.1029/2007JC004251.

Smith, W.O., Ainley, D.G., Cattaneo-Vietti, R., 2007. Trophic interactions within the Ross Sea continental shelf ecosystem. Phil. Trans. Roy. Soc. B 362, 95–111.

Southwell, C., Paxton, C.G.M., Borchers, D., Boveng, P., de la Mare, W., 2008. Taking account of dependent species in management of the Southern Ocean krill fishery: estimating crabeater seal abundance off East Antarctica. J. Appl. Ecol. 45, 622–631.

Squire, V.A., 2007. Of ocean waves and sea-ice revisited. Cold Regions Sci. Technol. 49 (2), 110–133.

Squire, V.A., Wadhams, P., Moore, S.C., 1986. Surface gravity wave processes in the winter Weddell Sea. Eos Trans. Am. Geophys. Union 67 (44), 1005.

Stammerjohn, S.E., Drinkwater, M.R., Smith, R.C., Liu, X., 2003. Ice–atmosphere interactions during sea-ice advance and retreat in the western Antarctic Peninsula region. J. Geophys. Res. 108 (C10). doi:10.1029/2002JC001543.

Stammerjohn, S.E., Martinson, D.G., Smith, R.C., Yuan, X., Rind, D., 2008a. Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–southern oscillation and southern annular mode variability. J. Geophys. Res. 113, C03S90. doi:10.1029/2007JC004269.

Stammerjohn, S.E., Martinson, D.G., Smith, R.C., Iannuzzi, R.A., 2008b. Sea ice in the western Antarctic Peninsula region: spatio-temporal variability from ecological and climate change perspectives. Deep Sea Res. II 55. doi:10.1016/j.dsr2.2008.04.026.

Steig, E., Scheider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C., Shindell, D.T., 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature. doi:10.1038/nature07669.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T., Serreze, M., 2007. Arctic sea ice decline: faster than forecast. Geophys. Res. Lett. 34, L09501. doi:10.1029/2007GL029703.

Sturm, M., Massom, R.A., 2009. Snow and sea ice. In: Thomas, D.G., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 153–204.

Tamura, T., Ohshima, K.I., Nihashi, S., 2008. Mapping of sea ice production for Antarctic coastal polynyas. Geophys. Res. Lett. 35, L07606. doi:10.1029/2007GL032903.

Thomas, D.N., Papadimitriou, S., Michel, C., 2009. The biogeochemistry of sea ice. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford, pp. 267–302.

Thomas, D.P., DeMaster, D.P., 1983. Parameters affecting survival of Weddell seal pups (*Leptonychotes weddelli*) to weaning. Can. J. Zool. 61 (99), 2078–2083.

Thompson, D.W.J., Solomon, S., 2002. Interpretation of recent Southern Hemisphere climate change. Science 296, 895–899.

Trathan, P.N., Forcada, J., Murphy, E.J., 2007. Environmental forcing and Southern Ocean marine predator populations: effects of climate change and variability. Phil. Trans. Roy. Soc. B 362, 2351–2365.

Tréguer, P., Pondaven, P., 2002. Climatic changes and the carbon cycle in the Southern Ocean: a step forward. Deep Sea Res. II 49 (9–10), 1597–1600.

Tremblay, J.-E., Smith Jr., W.O., 2007. Phytoplankton processes in polynyas. In: Smith Jr., W.O., Barber, D.G. (Eds.), Polynyas: Windows to the World's Oceans. Elsevier, Amsterdam, pp. 239–270.

Turner, J., 2004. The El Niño Southern Oscillation and Antarctica. Int. J. Climatol. 24 (1), 1–31.

Turner, J., Bindschadler, R., Convey, P., di Prisco, G., Fahrbach, E., Gutt, J., Hodgson, D., Mayewski, P., Summerhayes, C. (Eds.), 2009a. Antarctic Climate Change and the Environment. Scientific Committee on Antarctic Research, Scott Polar Res. Inst., Cambridge, p. 526.

Turner, J., Comiso, J.C., Marshall, G.J., Lachlan-Cope, T.A., Bracegirdle, T., Maksym, T., Meredith, M.P., Wang, Z., Orr, A., 2009b. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys. Res. Lett. 36, L08502. doi:10.1029/2009GL037524.

Tynan, C.T., 1998. Ecological importance of the southern boundary of the Antarctic Circumpolar Current. Nature 392, 708–710.

Tynan, C.T., Ainley, D.G., Stirling, I., 2009. Sea ice: A critical habitat for polar marine mammals and birds. In: Thomas, D.N., Dieckmann, G.S. (Eds.), Sea Ice, second ed.). Wiley-Blackwell, Oxford.

Vacchi, M., La Mesa, M., Dalu, M., MacDonald, J., 2004. Early life stages in the life cycle of Antarctic silverfish, *Pleuragramma antarcticum* in Terra Nova Bay, Ross Sea. Antartic Sci. 16 (3), 299–305.

van den Broeke, M., van de Berg, W., Meijgaard, E., 2006. Snowfall in coastal West Antarctica much greater than previously assumed. Geophys. Res. Lett. 33, L02505.

Vaughan, D.G., Marshall, G.J., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., King, J.C., Pudsey, C.J., Turner, J., 2003. Recent rapid regional climate warming on the Antarctic Peninsula. Clim. Change 60, 243–274.

Vernet, M., Martinson, D., Iannuzzi, R., Stammerjohn, S., Kozlowski, W., Sines, K., Smith, R., Garibotti, I., 2008. Primary production within the sea-ice zone west of the Antarctic Peninsula: sea ice, summer mixed layer, and irradiance. Deep Sea Res. II 55. doi:10.1016/j.dsr2.2008.05.021.

Wadhams, P., 2000. Ice in The Ocean. Gordon and Breach Science Publ., Reading, Australia, 351 pp.

Weeks, W.F., Ackley, S.F., 1986. Growth, structure and properties of sea ice. In: Untersteiner, N. (Ed.), The Geophysics of Sea Ice. NATO ASI Series 3, vol. 146. Plenum, pp. 9–153.

Weimerskirch, H., Inchausti, P., Guinet, C., Barbraud, C., 2003. Trends in bird and seal populations as indicators of a system shift in the Southern Ocean. Antartic Sci. 15, 249–256.

Wilson, P.R., Ainley, D.G., Nur, N., Jacobs, S.S., Barton, K.J., Ballard, G., Comiso, J.C., 2001. Adélie penguin population change in the Pacific sector of Antarctica: relation to sea-ice extent and the Antarctic circumpolar current. Mar. Ecol. Progr. Ser. 213, 301–309.

Woehler, E.J., Penney, R.L., Creet, S.M., Burton, H.R., 1994. Impacts of human visitors on breeding success and long-term population trends in Adélie penguins at Casey, Antarctica. Polar Biol. 14, 269−274.

Worby, A.P., Comiso, J.C., 2004. Studies of the Antarctic sea ice edge and ice extent from satellite and ship observations. Rem. Sens. Environ. 92, 98−111.

Worby, A., Markus, T., Steer, A., Lytle, V., Massom, R., 2008. Evaluation of AMSR-E snow depth product over East Antarctic sea ice using in situ measurements and aerial photography. J. Geophys. Res. 113, C05S94. doi:10.1029/2007JC004181.

Wu, X.R., Budd, W.F., Jacka, T.H., 1999a. Simulations of southern hemisphere warming and Antarctic sea-ice changes using global climate models. Ann. Glaciol. 29, 61−65.

Wu, X., Budd, W.F., Lytle, V.I., Massom, R.A., 1999b. The effect of snow on Antarctic sea ice simulations in a coupled atmosphere-sea ice model. Clim. Dynam. 15, 127−143.

Yuan, X., 2004. ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. Antartic Sci. 16 (4), 415−425.

Zhang, J., 2007. Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. J. Clim. 20, 2515−2529. doi:10.1175/JCLI4136.1.

Zwally, H.J., Yi, D., Kwok, R., Zhao, Y., 2008. ICESat measurements of sea ice freeboard and estimates of sea ice thickness in the Weddell Sea. J. Geophys. Res. 113, C02S15. doi:10.1029/2007JC004284.