A review of the scientific knowledge of the seascape off Dronning Maud Land, Antarctica

Lowther, Andrew

2022-08

REVIEW

A review of the scientific knowledge of the seascape off Dronning Maud Land, Antarctica

Andrew Lowther[1] · Cecilie von Quillfeldt[1] · Philipp Assmy[1] · Laura De Steur[1] · Sebastien Descamps[1] · Dmitry Divine[1] · Synnøve Elvevold[1] · Matthias Forwick[2] · Agneta Fransson[1] · Alexander Fraser[3] · Sebastian Gerland[1] · Mats Granskog[1] · Ingeborg Hallanger[1] · Tore Hattermann[1] · Mikhail Itkin[1] · Haakon Hop[1] · Katrine Husum[1] · Kit Kovacs[1] · Christian Lydersen[1] · Kenichi Matsuoka[1] · Arto Miettinen[4] · Geir Moholdt[1] · Sebastien Moreau[1] · Per Inge Myhre[1] · Lisa Orme[5] · Olga Pavlova[1] · Ann Helene Tandberg[6]

Abstract

Despite the exclusion of the Southern Ocean from assessments of progress towards achieving the Convention on Biological Diversity (CBD) Strategic Plan, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has taken on the mantle of progressing efforts to achieve it. Within the CBD, Aichi Target 11 represents an agreed commitment to protect 10% of the global coastal and marine environment. Adopting an ethos of presenting the best available scientific evidence to support policy makers, CCAMLR has progressed this by designating two Marine Protected Areas in the Southern Ocean, with three others under consideration. The region of Antarctica known as Dronning Maud Land (DML; 20°W to 40°E) and the Atlantic sector of the Southern Ocean that abuts it conveniently spans one region under consideration for spatial protection. To facilitate both an open and transparent process to provide the vest available scientific evidence for policy makers to formulate management options, we review the body of physical, geochemical and biological knowledge of the marine environment of this region. The level of scientific knowledge throughout the seascape abutting DML is polarized, with a clear lack of data in its eastern part which is presumably related to differing levels of research effort dedicated by national Antarctic programmes in the region. The lack of basic data on fundamental aspects of the physical, geological and biological nature of eastern DML make predictions of future trends difficult to impossible, with implications for the provision of management advice including spatial management. Finally, by highlighting key knowledge gaps across the scientific disciplines our review also serves to provide guidance to future research across this important region.

Keywords Antarctica · Biophysics · Knowledge · Dronning Maud Land · Marine · Spatial management

Introduction

The Southern Ocean (SO), one of the five oceans of the World (International Hydrographic Organization) connects the three major oceans through the largest ocean current on Earth, the Antarctic Circumpolar Current (ACC). The SO plays a crucial role in the global climate system, being a major CO_2 sink responsible for 40% of the anthropogenic CO_2 uptake by the worlds ocean (Sabine et al. 2004, 2013; Khatiwala et al. 2009; Frölicher et al. 2015; Landschützer et al. 2015) with the largest net sink in the vast sub-Antarctic

zone on the northern flank of the ACC (Sallée et al. 2012). Its northernmost boundary is not defined but can range from the northern front of the Antarctic Circumpolar Current at approximately 50°S up to 60°S, which is the definition suggested by International Hydrographic Organization.

Unlike the boreal high latitude oceans, the SO has displayed comparatively little warming in recent decades likely due to the meridional overturning circulation at its northern boundary, which draws cold deep water up to the surface and dampens the effects of surface heat uptake (Armour et al. 2016; Morley et al. 2020; Auger et al. 2021). This large-scale stability is in stark contrast to the impacts of climate change at more regional scales such as on the nearshore marine environments, with thinning and collapsing ice shelves and glacier retreat being increasingly attributed to

✉ Andrew Lowther
  Andrew.Lowther@npolar.no

Extended author information available on the last page of the article

rising air temperatures (particularly in the western Antarctic Peninsula) and upwelling of relatively warm Circumpolar Deep Water onto the continental shelf (Jenkins et al. 2018) Changing ocean temperatures are not the only pressure the SO is facing; ocean acidification is projected to further drive the potential range contraction of key species such as Antarctic krill *Euphausia superba* (Kawaguchi et al. 2013) ; the impacts of fishing pressure for Antarctic krill and to a lesser extent toothfish (*Dissostichus* spp.) on foodweb structure and function are poorly understood (Marschoff et al. 2012), as are both the implications of a questionable recovery of historically overfished species (Welsford 2011) and the documented recovery of upper trophic predators such as Antarctic fur seals (*Arctocephalus gazella*) and cetaceans (Branch et al. 2004; Kock 2007).

The suite of biodiversity conservation "Aichi" Targets agreed to within the Convention on Biological Diversity (CBD) includes a commitment to protect 10% of the global coastal and marine environment through a representative system of protected areas and other area-based management approaches by 2020 (Barnes 2015; Leadley et al. 2017; Chown et al. 2017), and more recent calls to increase this level of protection to ~30% by 2030 as part of the UK-led Global Ocean Alliance "30by30 Initiative" (https://www.gov.uk/government/topical-events/global-ocean-alliance-30by30-initiative/about). However, the SO is excluded from assessments of progress towards achieving the CBD Strategic Plan, including Aichi Biodiversity Target 11 (Chown et al. 2017). Under the Antarctic Treaty System (ATS), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has taken on the mantle of progressing efforts to achieve the CBD Strategic Plan. The ability to place the impacts of the multitude of stressors into a broader ecosystem context that is useful for policy-making bodies such as CCAMLR is driven by the availability of information on how the ecosystem has varied over time. Unfortunately, long-term time series amenable to this are scarce in the SO which hinders our ability to make empirical statements on ecosystem status and variability (Constable et al. 2016). In this regard, modelling has become a popular toolset to support management and policy decisions within national legislature and international treaties (Fulton 2010). Modelling efforts can integrate a wide range of biogeochemical and physical information in a common framework, highlight major processes, identify key knowledge gaps and provide a mechanism for examining management actions in a theoretical context prior to implementation (Fulton et al. 2015). In terms of developing the best available scientific understanding of ecosystem structure and function, the selection and implementation of an appropriate modelling approach is driven by the availability of data (Fulton 2010).

Adopting an ethos of presenting the best available scientific evidence to support policy makers at CCAMLR in designating spatial conservation measures, CCAMLR established the world's first high-seas Marine Protected Area (MPA), the South Orkney Islands Southern Shelf MPA in 2009 (Fig. 1) (Trathan and Grant 2019). Subsequent to this, a more systematic approach to circum-Antarctic spatial planning was developed and underpinned by a benthic bioregionalization analysis of the best available data (Douglass et al. 2014) and then formalized under Conservation Measure 91–04 as a means to guide how spatial planning be undertaken (Brooks et al. 2020). This analysis partitioned the Convention area into nine discrete Planning Domains (Fig. 1) to ensure that CCAMLR-designated MPAs achieved a broad regional and representative coverage. Since the designation of the MPA Planning Domains, the Ross Sea Regional Marine Protected Area (RSRMPA) came into practice in 2017 (1.5 M km^2; (Brooks et al. 2020) (Fig. 1). Other potential MPA's have been proposed across Domain 7 in East Antarctic (East Antarctic MPA, EAMPA; https://www.antarctica.gov.au/about-antarctica/law-and-treaty/ccamlr/marine-protected-areas/eampa/) and Domain 1 across the western Antarctic Peninsula and Scotia Sea (D1MPA; (Sylvester and Brooks 2020).

Available infrastructure, finances and the harsh climate all serve to limit the capacity to collect information either directly through ship campaigns or indirectly using autonomous platforms and satellite-derived data. Importantly, the spatial distribution of collected data is not uniform. Intuitively then, developing a science-based understanding of the ecosystem in the SO that is appropriate and useful for policy makers to develop area-based management strategies cannot rely on a single common analytical framework. Rather it must be achieved by using appropriate modelling tools supported by quality-controlled data which are then assessed for the level of confidence they provide (Fulton et al. 2015). This is possibly best exemplified by the very different analytical processes used in the development of the RSRMPA (benthic and pelagic bioregionalization with mass balanced foodweb model Pinkerton et al. 2010a; Sharp et al. 2010), EAMPA (bioregionalization and supported by important areas for upper trophic predators Raymond et al. 2015; Wenzel et al. 2016), and D1MPA (MARXAN spatial planning tools) chosen based on the varying degrees of data availability and quality.

A third MPA is also under development throughout CCAMLR Domains 3 and 4, which is being led and developed by Germany (on behalf of the European Union and its Member States) and Norway, with a growing list of co-proponents which at the time of publication included Australia, India, Korea, New Zealand, Ukraine, United Kingdom, Uruguay and the United States of America (Teschke et al. 2021). The area under consideration spans the Weddell, Lazarev, Riiser-Larsen and Cosmonaut Seas (the latter three seas are also collectively referred to as the Kong Haakon VII Hav),
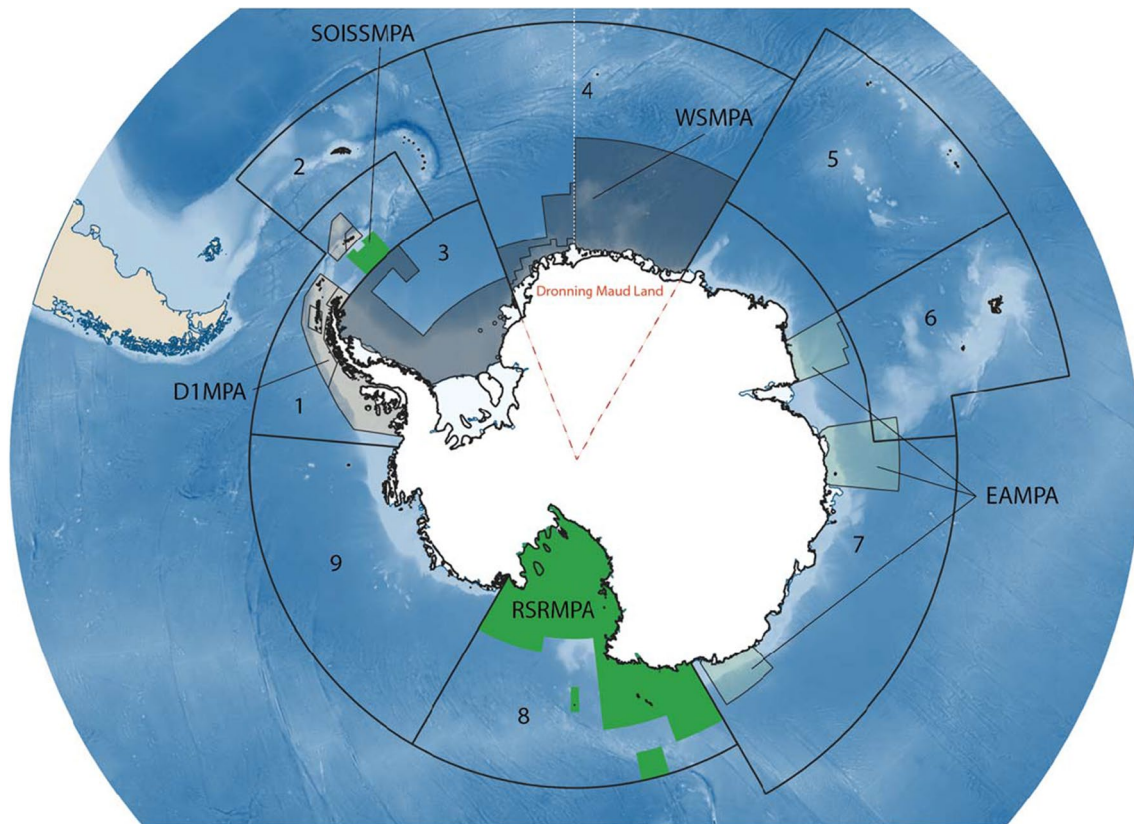
Fig. 1 The nine Marine Protected Area (MPA) planning Domains (numerical values within each Domain) designated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) after a bioregionalization analyses of the best available scientific data (Douglass et al. 2014). Red hatched lines correspond to the region known as Dronning Maud Land (DML) and our review focusses on the marine environment off this section of coastline. Domain 1 contains the first MPA to be designated within the CCAMLR Planning Domains (the South Orkney Islands Southern Shelf MPA; solid green, SOISSMPA), whilst Domain 8 hosts the world's largest MPA, the Ross Sea Regional MPA (green solid area, RSRMPA). There are three additional MPA proposals currently under consideration by CCAMLR; one led by Australia and the Euro-pean Union in Domain 7 (East Antarctic MPA; green hatched area, EAMPA) and one in Domain 1 co-proposed by Argentina and Chile (grey hatched area, D1MPA), which also corresponds to the area in which the krill fishery primarily operates. The third MPA proposal, led by the European Union and its Member States and Norway, spans Domains 3 and 4 (Weddell Sea MPA; grey hatched area, WSMPA—boundaries within the current iteration of the broader MPA are described in detail in Teschke et al. (2021)). Differences in data abundance across the Prime Meridian have led to a two-phased approach to developing this latter proposal with the area to the west of the Prime Meridian (white dashed line) considered mature enough for agreement, whilst to the east additional work is required

bounded to its east and west by the EAMPA and D1MPA proposals, respectively. Within this region, the German and South African Antarctic Research Programmes have a long history of scientific research of the Southern Ocean, each operating icebreaking ships to conduct scientific research and logistical support of their all-year Antarctic stations (Neumayer III and SANAE, respectively) for over forty years. There are four other nations that maintain a year-round presence through Antarctic stations in the Weddell Sea / Dronning Maud Land (DML) area (Troll, Norway; Maitri, India; Syowa, Japan; Novolazarekskaya, Russia: Fig. 2) and an additional seven summer-only research stations operated by Belgium (Princess Elizabeth), Finland (Aboa), Germany (Kohnen), Norway (Tor), Sweden (Svea, Wasa) and Japan (Asuka); however, none of these have had

vessels dedicated to marine research in recent history. Whilst remotely sensed environmental data from satellites, ocean moorings and other autonomous platforms provide data, early on in the process of developing the scientific understanding of the region it became clear that the vastly different levels of ship-based research effort had created an unbalanced distribution of physical, biogeochemical and trophic data across this region (Fig. 2). The western region from the prime meridian to the eastern side of the Antarctic Peninsula has been the focus of mainly German, British and Norwegian scientific expeditions resulting in a comprehensive scientific understanding of the region that is amenable to a similar MARXAN spatial planning exercise as conducted by the proponents of the D1MPA. However, the area to the east of the meridian out to the western boundary of
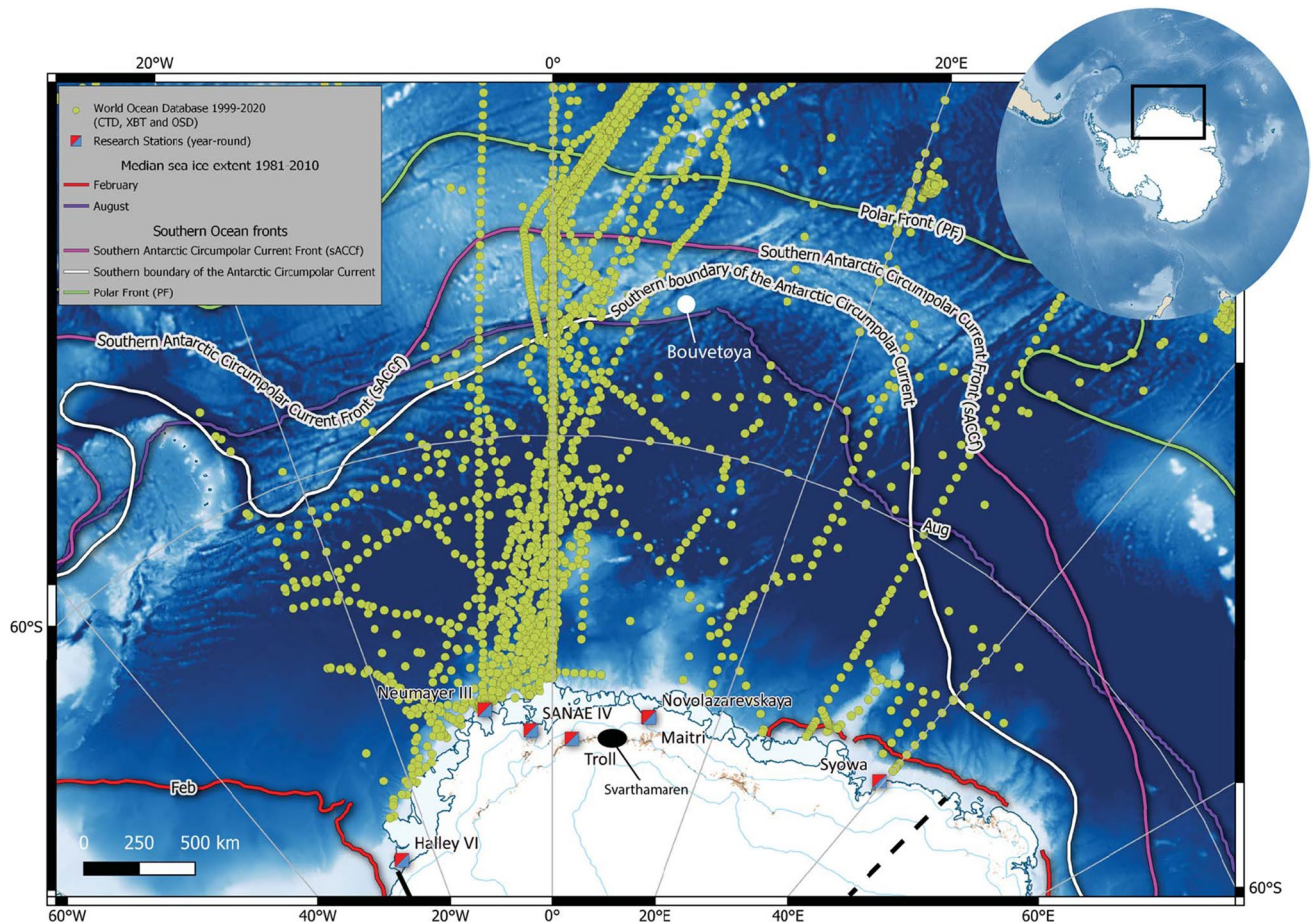
Fig. 2 The marine environment out from Dronning Maud Land (DML; bounded by black line) within the Atlantic Sector of the Southern Ocean (inset). Six year-round research stations are indicated, whereas seven additional summer-only stations within DML are not shown (for image clarity). There is considerable seasonal variability in median sea ice extent that can reach almost as far north as Bouvetøya and the Antarctic Polar Front (PF—solid green line) during the winter (solid purple line). World Ocean Database Conductiv-ity Temperature and Depth (CTD), Ocean Station Data (OSD) and Expendable Bathythermograph (XBT) data within this marine region between 1999–2020 are shown (yellow dots) to exemplify the degree of data disparity on either side of the Prime Meridian (0° longitude). Our review focusses on the physical, geochemical and biological data across the marine environment adjacent to DML, generally as far north as the PF

the EAMPA has received comparatively less research attention and consequently requires the application of a less data-intensive modelling approach. To ensure that appropriate and robust scientific advice could be given, the proponents of the MPA agreed to adopt different modelling approaches to characterize the ecosystem in the west versus east (across this data imbalance) whilst ensuring that the outputs could be harmonized in order to make sense for management and policy-making purposes.

The region of Antarctica known as Dronning Maud Land (DML) and the Atlantic sector of the Southern Ocean (SO) that abuts it ranges from 20°W to 45°E (Fig. 1), conveniently span key geographic regions under management consideration and it is this region that we focus on herein. We refrain from setting a latitudinal boundary for the northern extent of our review given both the challenges in delimiting the

SO we describe earlier, and to maintain a degree of flexibility in describing large-scale processes. We review the body of physical, geochemical and biological knowledge of the marine environment that has been generated throughout this region. In conducting our review, we address two key aims (1) to provide a transparent scientific backdrop to place ongoing management work into context, particularly with respect to future MPA planning activities and (2) to give guidance for the direction of potential research needs that could be used to stimulate future collaborative science programmes in the region.

Physical system

Paleoceanography

In the Atlantic sector of Antarctica, several paleoceanographic records have been established from the Antarctic Peninsula (Taylor et al. 2001; Shevenell et al. 2011; Hass et al. 2016; Allan et al. 2020) with others around Bouvetøya (Bianchi and Gersonde 2004; Divine et al. 2010) and the Scotia Sea (Allen et al. 2011; Collins et al. 2013). However, there are comparatively few reconstructions from the DML region. A continuous record covering the time range 1.35 million years (My) to eight thousand years (ky) before present (BP) from the continental margin off DML showing a linkage of oceanographic changes to fluctuations of North Atlantic Deep Water formation and the Atlantic Meridional Overturning Circulation (Forsberg et al. 2003). The record also clearly reflects the Mid-Pleistocene Transition around 1.25–0.7 My when the duration of glacial-interglacial cycles changed from ca. 40 to 100 ky (Lisiecki and Raymo 2005; Clark et al. 2006).

During the Last Glacial Maximum (LGM) ca. 30–20 ky BP, diatom-based reconstructions from south of the Antarctic Polar Front (PF) in the Atlantic sector of Antarctica indicate that the last glacial summer SSTs were 1–3 °C colder than modern conditions (Xiao et al. 2016). The last glacial ended with a two-step warming, although this warming was suppressed towards the south by ice discharge from Antarctica (Xiao et al. 2016). During the deglaciation, between 16 and 14.5 ky BP, a slowing in the rate of warming in the Atlantic sector of the SO, including the seas offshore DML, decreased concurrently with a reduced rate of CO_2 increase in the atmosphere and a minor cooling over Greenland (Stenni et al. 2011).

For the last ca. 12 ky (Holocene interglacial period), the sparse diatom-inferred SST records from the vicinity of the PF show relatively gradual climate change for the Atlantic sector of the SO (Nielsen et al. 2004; Divine et al. 2010; Xiao et al. 2016). In this area, the warmest ocean surface conditions were characterized by SSTs 1–3 °C above modern mean temperatures and reduced sea ice presence between 12 and 9 ky BP. Subsequent cooling coincided with decreasing summer insolation at high northern latitudes during the mid to late Holocene (Divine et al. 2010; Xiao et al. 2016). However, some records show that the late Holocene warming in the APF region began shortly after 4.4 ky BP (Divine et al. 2010) and that it coincided with the climate optimum at the Antarctic Peninsula around 4–3 ky BP (Hjort et al. 1998). During the last 1.6 ky BP, warm SSTs comparable to the Early Holocene optimum prevailed in the APF of the Atlantic sector of the SO, and the Little Ice Age cooling of the Northern Hemisphere was not detected in this area (Hodell et al. 2001; Nielsen et al. 2004).
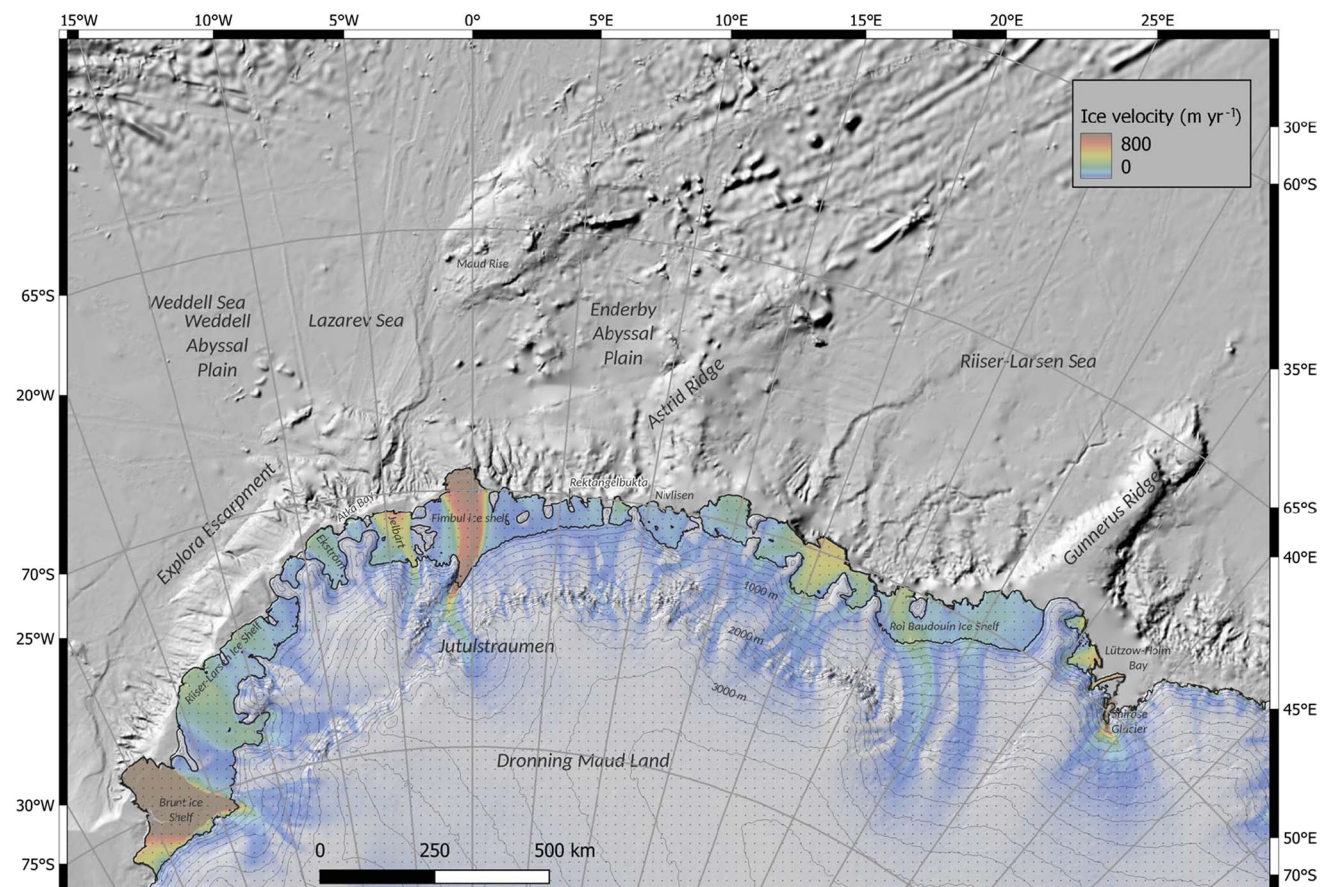
Ice shelves

The DML coast is dominated by ice shelves, which are floating extensions of the inland ice sheet (Fig. 3). The total area of DML ice shelves is ~ 221,000 km^2 or about 14% of the total for Antarctic ice shelves. Compared to other Antarctic regions, DML ice shelves are relatively small (typically ~ 100 km long/wide), they are bounded by promontories of the ice sheet and their current termini are near the break of the continental shelf. The thickness of the ice shelves ranges from a few hundred metres to a kilometre, with thickest ice near the grounding line of major ice streams and outlet glaciers (Fretwell et al. 2013; Morlighem et al. 2020) . The central parts of ice shelves are typically moving by several metres per day, whereas their sides can be nearly stagnant (Rignot et al. 2013).

Ice rises are locally grounded features within DML ice shelves, where ice-shelf flow is diverted around a topographic feature or as ice rumples when ice-shelf flow overrides the grounded feature (Matsuoka et al. 2015). Surface scars that appear in the middle of an ice shelf are typically related to local grounding and friction from ice rumples. Strong shearing and fracturing in these areas and along ice-shelf margins can cause heavy crevassing and rifting that can spread to large areas downstream, seen for example on the Jelbart (Humbert et al. 2015) and Fimbul ice shelves (Humbert and Steinhage 2011) and Shirase Glacier (Nakamura et al. 2010). Along-flow stripes and channels are typically advected from the grounding line where they have formed due to bedrock undulations and subglacial water outlets (Drews et al. 2017; Alley et al. 2018). These surface- and basal structures further evolve by localized ice-shelf strain and topographically induced basal melting/freezing and snow accumulation (Langley et al. 2014a; Berger et al. 2017; Drews et al. 2020). The implications of these surface- and basal structures on ice-shelf stability and mass balance have been a major research focus in recent years and the relevant processes need to be better parameterized in future ice-sheet models (Jansen et al. 2013; Borstad et al. 2017; De Rydt et al. 2018).

In general, DML ice shelves are in an advancing and growing phase until they calve off large icebergs with a retreated front as a result. The largest known calving event is that of Trolltunga on Fimbulisen where a 50×100 km iceberg broke off during the austral winter of 1967 (Swithinbank 1969) and spent a decade drifting westward along the coast to the Antarctic Peninsula with numerous breaks due to grounding on seamounts (Vinje 1977). In a similar pattern, many icebergs can be observed drifting or grounded along the coast of DML, both local ones and icebergs that originate

Fig. 3 Overview of glaciology and ocean bathymetry in Dronning Maud Land. Ice shelves are outlined in black and nunatak areas are shaded. Ice flow velocity (Gardner et al. 2018) is shown in colours on top of the Landsat Image Mosaic of Antarctica (Bindschadler et al. 2008). Ice sheet topography is visualized with 200 m contour lines (Helm et al. 2014) and ocean bathymetry is shown as a shaded relief (Arndt et al. 2013)

from as far east as the Ross Sea (Pirli et al. 2015). Compared to the rest of Antarctica, DML has been identified as a region with particularly infrequent calving and large iceberg sizes (Liu et al. 2015). This makes it complicated to interpret ice-shelf extent in a climate context, so it is more common to focus on changes in ice thickness as a measure of ice-shelf condition. In contrast to West Antarctica where many ice shelves have been thinning rapidly, DML ice shelves have experienced a slight thickening over the last few decades (Paolo et al. 2015). Thickening has also been observed in the inland and over ice rises in DML (Goel et al. 2018; Smith et al. 2020). The apparent pattern of ice thickening might be part of a long-term trend or related to a positive snowfall anomaly over the region that started in 2009 (Boening et al. 2012; Lenaerts et al. 2013). Observations of snow accumulation on DML ice shelves show typical values of 0.2–0.6 m water equivalent per year (Sinisalo et al. 2013; Pratap et al. 2022) , but with higher variability around ice rises due to orographic snowfall and wind erosion (Lenaerts et al. 2014; Kausch et al. 2020). Long-term ice core records from the

coastal region indicate that snow accumulation over the last century has decreased in western DML (Altnau et al. 2015) and increased in eastern DML (Philippe et al. 2016).

Surface melting is small compared to snowfall, but occurs regularly on many DML ice shelves (Trusel et al. 2013), particularly in blue-ice areas where a combination of kata-batic winds and low albedo enhances melting (Winther et al. 1996; Lenaerts et al. 2017). Most meltwater refreezes locally in the snow and firn, but near-surface drainage into streams and lakes occur at ice shelves like Nivlisen and Roi Bau-douin (Kingslake et al. 2017; Dell et al. 2020). The ground-ing zone of Nivlisen also hosts several epishelf lakes which are freshwater tidal lakes between rocky land and an ice shelf with a connection to the ocean beneath the ice shelf (Gibson and Andersen 2002; Phartiyal et al. 2011). If surface melting of DML ice shelves increases due to global warm-ing, the firn pack might become saturated by ice (Hubbard et al. 2016) and start to contribute towards hydrofracturing and ice-shelf disintegration as seen on the Antarctic Penin-sula (Scambos et al. 2000; Alley et al. 2018). Surface- and

subglacial meltwater runoff might also become relevant processes for ice-sheet mass balance in the future (Bell et al. 2018).

Basal melting of ice shelves by ocean water is more widespread and of larger magnitude than surface melting. Over DML ice shelves, basal melt rates of up to a few metres per year have been measured locally by ice-penetrating radar (Langley et al. 2014b; Lindbäck et al. 2019) and inferred over larger areas by satellite remote sensing (Rignot et al. 2013; Berger et al. 2017). Basal melt rates are typically highest near ice-shelf grounding lines, where ice is thickest, as well as within basal channels and near the fronts where summer-warmed surface water can penetrate below the ice-shelf fronts (Hattermann et al. 2012). Basal refreezing has also been observed at several locations (Orheim et al. 1990; Pattyn et al. 2012), but is likely of small magnitude compared to the net basal melting which has been estimated to 75 Gt a^{-1} (Rignot et al. 2013), 145 Gt a^{-1} (Liu et al. 2015) and 158 Gt a^{-1} (Adusumilli et al. 2020) for DML as a whole. Seasonal and temporal variations in basal melting have been observed to be large (Lindbäck et al. 2019; Sun et al. 2019), but so far little is known about interannual variability and long-term trends in DML.

The discharge of ice across the grounding line to the DML ice shelves is estimated to be in the range 160–190 Gt a^{-1} (Rignot et al. 2013; Liu et al. 2015), with no significant change between 2008 and 2015 for the region as a whole (Gardner et al. 2017). This is consistent with other regions in East Antarctica, but in contrast to West Antarctica where several large glaciers have sped up (Mouginot et al. 2014) as a result of increased ice-shelf basal melting and consequent loss of buttressing (Pritchard et al. 2012). Ice-shelf changes at this scale are so far unheard of in DML, but local observations and modelling show that ungrounding of ice rumples can cause significant glacier acceleration (Favier et al. 2016; Gudmundsson et al. 2017). Seaward of the ice rises and rumples, the ice shelves play a more passive role and are expected to have little or no dynamic impact on the inland ice sheet, acting as a safety band for future ice-front retreat (Fürst et al. 2016).

Sea floor, shelf geology and bathymetry

The seafloor off DML was created along a mid-ocean ridge, the Southwest Indian Ridge (SWIR), which is the tectonic boundary between the African lithospheric plate to the north and the Antarctic lithospheric plate to the south (Online Resource 1). SWIR is characterized as a slow to ultraslow mid-ocean spreading ridge (Sauter et al. 2013), with spreading rates as low as 14 mm a^{-1}, amongst the slowest on Earth. The continental margin (including the continental shelf and slope) of DML has a rifted volcanic origin which formed during the break-up of Gondwana (Jokat et al. 2003).

Bathymetry data is sparse in the east of DML region, with the International Bathymetric Chart of the Southern Ocean (IBCSO) relying heavily on interpolation between empirical data (Arndt et al. 2013). Offshore from western DML is a narrow coastal shelf with water depths of < 600 m, a steep continental slope interrupted by a steep cliff (the Explora Escarpment, Fig. 3) before the Weddell Abyssal Plain is reached at ca. 4400 m (Michels et al. 2002). The shelf has canyons, such as the Wegener Canyon, ridges and depressions (Jerosch et al. 2016). The Weddell Abyssal Plain is generally flat, but it features the Maud Rise (Brandt et al. 2011a) and Astrid and Gunnerus Ridges (Fig. 3); Maud Rise is a large, equidimensional volcanic plateau in the Lazarev Sea which rises 2000 m above the seafloor; Astrid Ridge forms a pronounced north–south trending seafloor high, separating the Lazarev and Riiser-Larsen Seas; Gunnerus Ridge is a prominent bathymetric structure probably consisting of continental crust (Mizukoshi et al. 1986; Roeser et al. 1996) separating the Riiser-Larsen and Cosmonaut Seas.
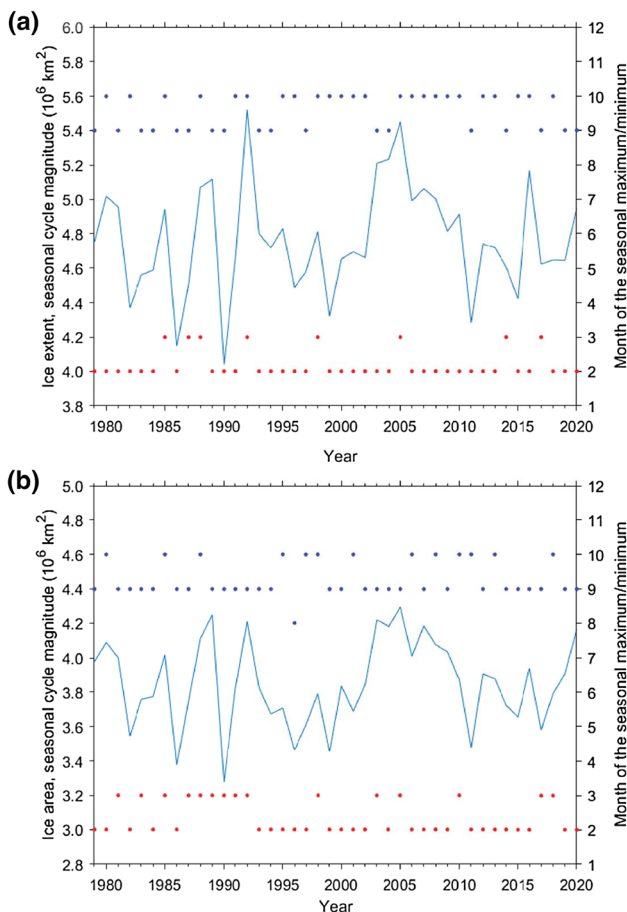
The marine part of the continental margin of DML is bordered by the grounding line and starts inland of the "coastline" defined by the ice shelf edge. Bathymetric surveys to the western limit of DML (southeast Weddell Sea) have revealed a channel-levee system; multiple channels merge into a larger channel flowing northeast towards DML (Kuhn and Weber 1993; Michels et al. 2002). A channel system in the Riiser-Larsen Sea extends from the upper continental slope towards the Enderby Abyssal Plain (Thiede and Oerter 2002; Hass et al. 2016). Bathymetry below the floating Fimbul ice shelf based on seismic surveys (Nøst 2004; Smedsrud et al. 2006) compiled as part of the Bedmap2 (Fretwell et al. 2013) and the Rtopo2 data sets (Schaffer et al. 2016) shows a relatively flat seafloor between 500 and 1000 m water depth. Seismic observations of bathymetry under ice shelves exist for Fimbulisen (Nøst 2004; Smedsrud et al. 2006) and Ekström Ice Shelf (Smith et al. 2020), and have been combined with airborne gravity data and modelling to coastal bathymetry maps for the main ice shelves of central DML (Eisermann et al. 2020, 2021). Remaining areas are covered by the bathymetry compilations Bedmap2 and Rtopo2. Most of these data show a relatively flat seafloor between 500 and 1000 m water depth. However, some deeply incised valleys are also present, the most prominent of which is beneath the Jutulstraumen ice stream (Fig. 3). Other main topographic features are the ice rises which rest on shallower beds, but typically grounded well below sea level (Goel et al. 2020). In terms of marine sedimentation, the thicknesses of sediment sequences vary from ~ 1000 m in the Lazarev Sea to ~ 2000 m in the Riiser-Larsen Sea, with the thickest sequences occurring in the east (Hinz et al. 2004).
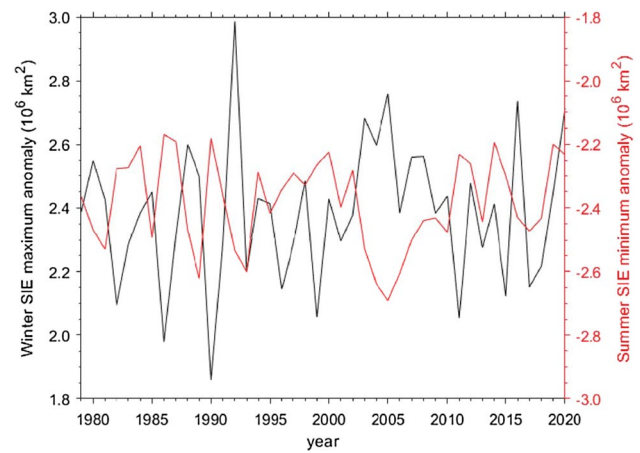
Sea ice off Dronning Maud Land

Landfast sea ice

Between 3 and 13% of Antarctic sea ice area (SIA) is land-fast ice depending on the season (Aoki 2017; Fraser et al. 2020) with the remainder being drifting sea ice. However, landfast ice protects the ice shelf edge from waves and is an important habitat for penguins and seals (Fraser et al. 2020, 2021). There are a limited number of studies in the DML region, such as those on break-up of landfast sea ice at Lützow-Holm Bay, eastern DML (e.g. Aoki 2017), and on landfast ice evolution in Atka Bay (Arndt et al. 2013, 2020) (Fig. 3). In the new circum-Antarctic landfast sea ice distribution data set from 2000 to 2018 (Fraser et al. 2020, 2021) the area off DML is found to be a region with rather low landfast ice extent compared with other regions along

Fig. 5 Anomalies of sea ice extent (SIE) winter maximum and summer minimum in the Dronning Maud Land sector of the Southern Ocean since 1979. Plots are derived from Special Sensor Microwave/Imager derived monthly mean sea ice concentrations

the Antarctic coast (see Figs. 3, 4 in Fraser et al. 2020). DML fast ice area varies within $1–7 \times 10^4$ km² comprising from nearly 30% (summer, February) to only about 1% (winter, September) of total sea ice area in the region (Figs. 4, 5). This might be linked to a generally deeper bathymetry (Fig. 2) and hence a less frequent presence of grounded icebergs that could provide the anchoring points for landfast ice off the coast of DML (Fraser et al. 2021). Noteworthy is that about half of the landfast ice in the 20° W to 40°E sector is located in the Lützow-Holm Bay area (between 33° and 40°E), and the reminder of the DML coastline has relatively little landfast ice.

Pre-satellite records of Antarctic sea ice extent variability

Our knowledge of Antarctic sea ice variability including DML for the period before 1979 remains fragmentary and largely based on early satellite records (Gallaher et al. 2015), paleorecords (Stenni et al. 2017; Thomas et al. 2019) and documents (e.g. ship logbooks). Whale catch positions have been used to infer the regional summer sea ice extent (SIE) retreat within 50°W–120°E by ca. 3–7° of latitude between 1931–1961 and 1971–1987 (de la Mare 1997; Cotté and Guinet 2007). A total decrease of 25% in Antarctic SIE may have occurred between these two periods, with the largest changes found for the DML region. However, pan-Antarctic sea ice maps of Hansen (1934, 1936) for 1929–1934 based on information from Norwegian whaling factories do not support such a drastic change. Accounts from earlier expeditions to Antarctica (1897–1917) provide additional evidence for a possible lack of secular trend in Antarctic summer SIE over the twentieth century. Historical sea ice conditions around Antarctica are comparable to the present

Fig. 4 Amplitudes of seasonal cycles of sea ice extent (**a**) and sea ice area (**b**) in the Dronning Maud Land sector of the Southern Ocean. Plots based on Special Sensor Microwave/Image monthly mean sea ice concentrations since 1979. The magnitude of seasonal cycle for each year is calculated using the method of Huang and Savage (1998). Blue (red) dots indicate the months when the seasonal maximum (minimum) of sea ice extent (**a**) and area (**b**) were registered

day except for the Weddell Sea area where a sea ice edge shift by 1.0–1.7° further north has been inferred (Edinburgh and Day 2016).

Antarctic sea ice extent and area off Dronning Maud Land during the satellite remote sensing era

Sea ice variability off the coast of DML is dominated by the seasonal cycle that represents some 97% of the total variance for both sea ice area (SIA) and SIE over the period 1979 to 2020. The seasonal cycle itself is highly variable with the amplitude changing from 4.0 to 5.6 million km^2 (Fig. 4a) and from 3.2 to 4.3 million km^2 for SIA (Fig. 4b), respectively. As a result, no significant changes and trends over this period for the study area were detected neither in SIE, nor SIA. The annual minimum SIE is typically reached in February, but occasionally in March (Fig. 4a). The seasonal timing of the winter SIE maximum is slightly more variable, varying from September to October, with the majority of maxima in October. Similar applies for SIA (Fig. 4b) though maximum SIA often tends to precede the SIE maximum, pointing to a role of a wind-forced drift in a final phase of the seasonal sea ice expansion and a relatively large sea ice velocity trend for the DML sector compared with most other Southern Ocean regions (Holland and Kwok 2012). Time-series of anomalies for the seasonal SIE and SIA extremes for the DML sector (Fig. 5) are significantly anticorrelated, pointing to influence of albedo and heat uptake feedbacks (Stammerjohn et al. 2012; Holland 2014).

Sea ice thickness in Dronning Maud Land

Information on thickness of Antarctic sea ice is still sparse. Pack ice thicknesses measured with the laser altimeter on ICESat in late 2003 were around 1 m off DML, whilst thickness estimates from ship-based observations were much thinner at approximately 0.5 m, or less (ASPeCt data, see http://aspect.antarctica.gov.au/data; Worby et al. 2008; Maksym et al. 2012). Spring ice thicknesses for the Weddell Sea and the westernmost part of DML measured from ICESat were in the range 1–2 m (Yi et al. 2011), whilst thicker sea ice in the Weddell Sea for years 2011, 2014 and 2016, averaged to 2.4–2.6 m based on recordings from airborne surveys (Operation IceBridge) (Kwok and Kacimi 2018). Strong interannual variability of ice thickness for pack ice off Lützow-Holm Bay has also been detected between 2000 and 2012, with a mean total thickness of 1.9 m (Sugimoto et al. 2016) .

Direct measurements of landfast ice thickness in Rektangelbukta in early summer between years 2005 and 2010 revealed a dominant mode in the range 1.50–1.75 m, and a broad range of snow thicknesses (dominant mode 0–0.2 m, but also occasionally large amounts of snow > 0.5 m) (Heil

et al. 2011). Ice thickness surveys in Atka Bay, over a 9-year period, showed that the ice thickness was about two metres (Arndt et al. 2020). In Lützow-Holm Bay fast ice thickness varied significantly between years, with significant contribution from snow to ice mass balance (Kawamura 1997), whilst Uto et al. (2006) revealed distinct first- and multi-year zones with thicknesses of 1–2 and 2–4 m, respectively. Snow-ice, from upward ice growth at the transition snow-ice due to flooding with seawater and refreezing, is widespread in the Antarctic ice pack (Lange et al. 1990; Eicken et al. 1994). Snow-ice is found in the DML region in both pack ice and landfast sea ice (Kawamura 1997) . Platelet ice, which can contribute to ice growth from below, has also been observed in DML (Hoppmann et al. 2015; Hunkeler et al. 2015; Arndt et al. 2020).

Physical oceanography

The regional oceanographic environment is characterized by the influence of the Weddell Gyre, a large cyclonic, wind-driven ocean gyre that connects the Antarctic Circumpolar Current (ACC) with the coastal circulation in the Atlantic sector of the Southern Ocean (Vernet et al. 2019) (Fig. 6). With a major site of Antarctic Bottom Water formation located in the southwest (Orsi et al. 1999; Meredith 2013), and comprising the World's largest contiguous region of deep upwelling in the interior (Marshall and Speer 2012; Talley 2013), the Weddell Gyre allows strong connections between the atmosphere, surface ocean, and deep waters. Its dimensional overturning circulation plays an important role for the biological and carbon cycle in the Southern Ocean (MacGilchrist et al. 2019) and has the capability of modulating global climate on time scales of hundreds to thousands of years, arguably being one of the most influential oceanic region on the planet (Vernet et al. 2019).

The southern, westward flowing part of the Weddell Gyre forms a topographically steered boundary current over the steep continental slope which converges with the shallower Antarctic Coastal Current that flows westward on the narrow continental shelf into the Weddell Sea (Fahrbach et al. 1992; Heywood et al. 2013). The eastern gyre inflows (Ansorge et al. 2015; Ryan et al. 2016) fuel this joint boundary current system with Circumpolar Deep Water, a relatively warm, saline, nutrient-rich and oxygen-depleted mid-depth water mass of tropical origin present in the ACC. On its way south, this water mass is transformed into a slightly colder derivative called Warm Deep Water (WDW), as it entrains the Weddell Gyre (Nicholls et al. 2009).

In principle, WDW has a large potential to melt the Antarctic Ice Sheet along the DML coast (Hattermann et al. 2014) and the Weddell Sea downstream (Hellmer et al. 2012, 2017), with direct consequences for global sea level (Timmermann and Goeller 2017). However, despite its proximity
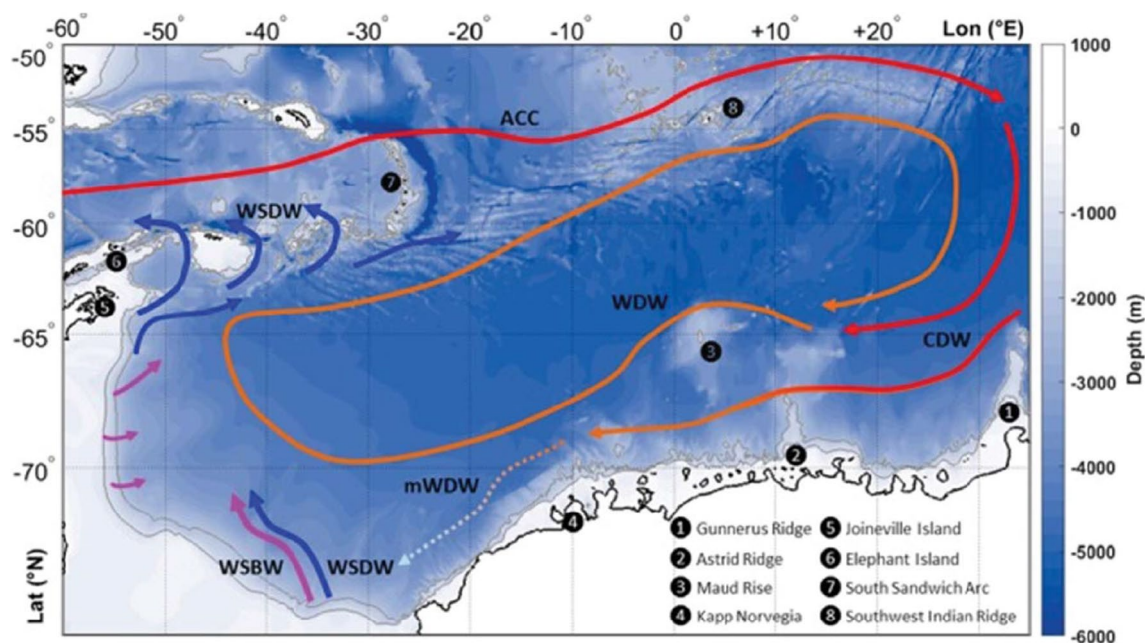
Fig. 6 The general circulation and pathways of water masses in the Weddell Gyre off the Dronning Maud Land coast (from Reeve et al. 2019). *ACC* Antarctic Circumpolar Current, *CDW* Circumpolar Deep Water; *(m)WDW* (modified)Warm Deep Water, *WSDW* Weddell Sea Deep Water, *WSBW* Weddell Sea Bottom Water

to the continent, the WDW is currently separated from the coast by the pronounced Antarctic Slope Front, shaped by prevailing easterly winds that set up a southward Ekman transport such that cold, fresh Antarctic Surface Water is transported onshore (Sverdrup 1954; Nøst et al. 2011) pushing the WDW down to 600–700 m depth (Heywood et al. 2013) (Fig. 7).

Coastal polynyas that are of great importance for local sea ice formation and biological productivity (Arrigo et al. 1997; Moreau et al. 2019) are typically smaller here than elsewhere around Antarctica (Tamura et al. 2016) and bottom water formation usually does not occur in this region (Fahrbach et al. 1994). Instead, the convergence of sea ice melt water along the DML coast, associated with the easterly winds (Hattermann et al. 2012; Zhou et al. 2014), gives rise to a cold and "fresh shelf regime" (Thompson et al. 2018) that contrasts with the dense water masses produced by sea ice export on the wide southern Weddell Sea continental shelf (Nicholls et al. 2009) and the warmer continental shelf regions in west Antarctica (Jenkins et al. 2018).

Whilst the coherent along-slope boundary currents propagate oceanic signals over long distances along the Antarctic margin (Graham et al. 2013) prominent topographic features, such as Gunnerus and Astrid Ridge and the undersea Maud Rise affect the local circulation (de Steur et al. 2007; Dong et al. 2016) and can influence the presence and timing of sea ice, and biological productivity in this region (Kauko et al. 2021). Maud Rise in particular, plays a role in the

intermittent appearance of the Weddell Polynya (Gordon 1978; Campbell et al. 2019; Francis et al. 2019) that is associated with the strength of the westward flow impinging on the seamount (Holland 2001).

Many open questions of the ocean, climate and marine ecosystem off the DML coast depend on a better understanding of the interaction of the narrow continental shelf regime with the deep ocean circulation of the Weddell Gyre (Vernet et al. 2019). The effect of melting of DML ice shelves on the water masses of the Weddell Gyre in a changing climate, and vice versa, plays key role for the circulation in this sector of Antarctica (Hattermann 2018) and, thus, important for predicting future sea levels (Hellmer et al. 2017). Whilst the main physical processes that mediate the energy and mass fluxes from the deep ocean and across the Antarctic Slope Front are known, including surface Ekman dynamics (Hayakawa et al. 2012), mesoscale eddies (Nøst et al. 2011; Stewart and Thompson 2015; Thompson et al. 2018), local topographic interactions (Price et al. 2007; St-Laurent et al. 2013), tides (Sun et al. 2019) and undercurrent dynamics (Chavanne et al. 2010).

Shipboard hydrographic data are mostly available for the (eastern and southern) Weddell Sea, whilst only sporadic observations from the Weddell Gyre east of the prime meridian are available (Ryan et al. 2016). Increasing availability of (sea ice tracking) Argo floats has boosted the coverage in the interior gyre (Reeve et al. 2019; Moreau et al. 2020), and
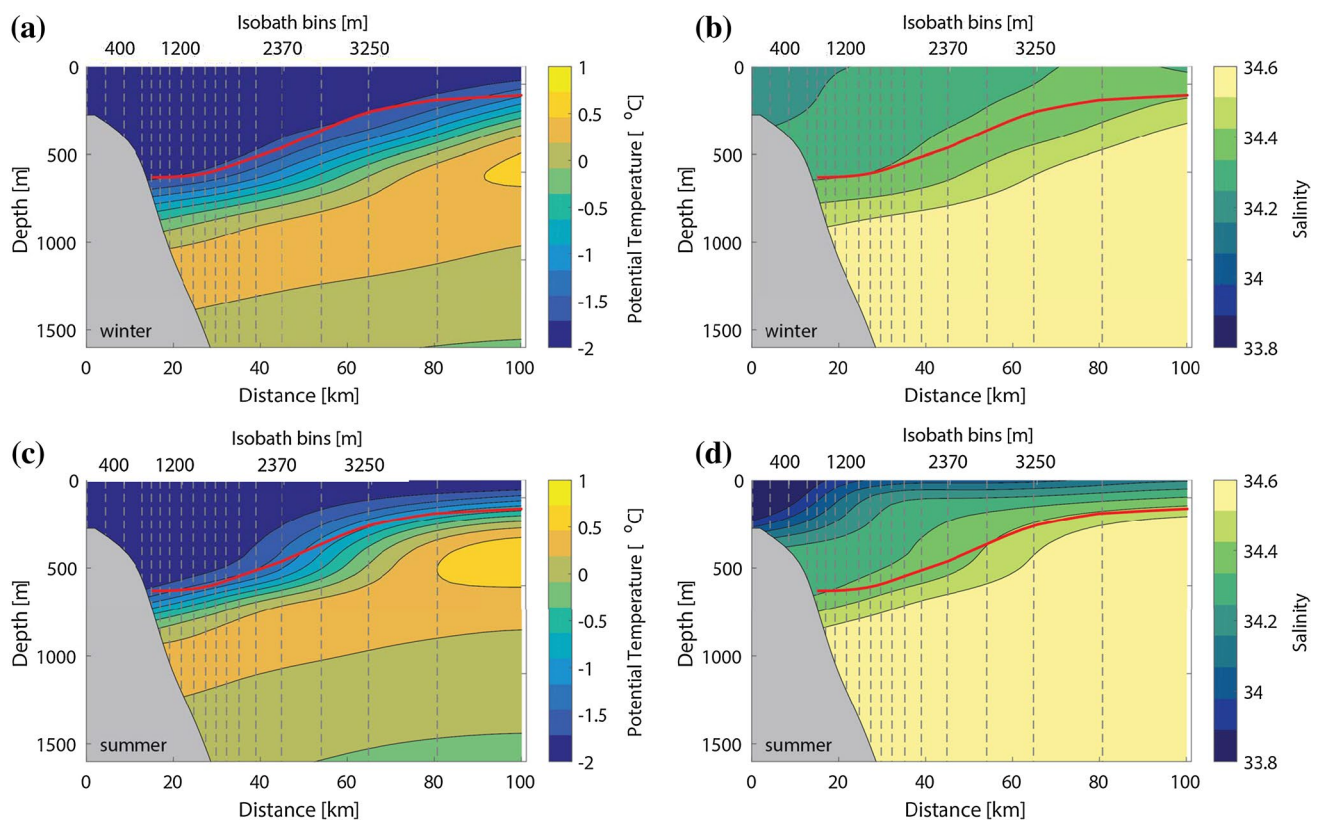
Fig. 7 Vertical cross sections of the Antarctic Slope Front (ASF) in the reduced-salinity shelf regime along the DML coast Sea at approximately 17°W. Seasonal climatologies of winter (July–December) and summer (January–June) of (**a**), (**c**) potential temperature and (**b**), (**d**) salinity constructed from > 2800 ship-based and sensor-equipped seal hydrographic profiles and projected onto standard cross section. Dashed vertical lines indicate the spacing of individual depth bins as described in Hattermann (2018); the red curve shows the average thermocline depth as a constant reference in each panel

the dawn of animal-sensor based hydrographic observations (Roquet et al. 2013) helps to fill in the Southern Ocean data desert. However, the general lack of coastal observations (Jourdain et al. 2019) and severe summer bias (Hattermann et al. 2018) limit our understanding of the dynamics at the gyre margin (Reeve et al. 2019). Dedicated, year-round, as well as long-term observational efforts are needed to better understand and forecast the physical processes that affect various aspects of the marine environment in the DML region.

Biogeochemical system

Air-sea CO$_2$ fluxes, ocean acidification and biogeochemical drivers

The marine environment of DML is physically and chemically a dynamic area due to the interaction between bathymetric features, frontal systems, sea ice edges and zones, ice shelves and variability in biogeochemical processes (Bakker et al. 1997; Bathmann et al. 1997; Chierici et al.

2004; Fransson et al. 2004a, b; Landschützer et al. 2015). The variability in these features and processes has a large impact on sea-air CO$_2$ exchange and vertical carbon export on diurnal, seasonal and interannual scales (Hoppema et al. 1999, 2000; Chierici et al. 2004; Fransson et al. 2004a; Metzl et al. 2006). The seasonal cycle is the dominant factor of the variability of partial pressure of CO$_2$ (pCO$_2$) in the Southern Ocean, with net outgassing of CO$_2$ being dominant during winter and biological uptake during summer (Metzl et al. 1999; Fransson et al. 2004a; Lenton et al. 2013; Monteiro et al. 2015). Biological uptake of CO$_2$ is enhanced at fronts, in the ACC (Chierici et al. 2004) and in the marginal sea ice zone (Froneman 2004; Arrigo et al. 2008) due to the availability of essential macro-nutrients and iron, and surface-water stratification (de Baar et al. 1995; Bathmann et al. 1997; Bathmann 1998; Chierici et al. 2004; Arrigo et al. 2008; Tagliabue et al. 2014; Graham et al. 2015). In the eastern Weddell Sea, the relatively warm and CO$_2$-rich Circumpolar Deep Water (CDW) is transported upwards in the water column affecting the ocean chemistry and increasing surface CO$_2$ and ocean acidification (Hoppema et al. 1995; Bakker et al. 1997; Chierici et al. 2004; Fransson

et al. 2004b; Pretorius et al. 2014) . Moreover, direct pCO$_2$ measurements obtained in early winter under the ice of the Weddell Sea, combined with estimated entrainment rates, showed that an area of intense upwelling expressed by the structure of the cyclonic gyre has the capability to be almost continuously a sink for atmospheric CO$_2$ (Stoll et al. 1999; Hoppema 2004a, b; Van Heuven et al. 2014). Moreover, in DML, autumn surface pCO$_2$ observations showed the largest ocean CO$_2$ uptake in the region, particularly near the ice-covered coast of DML (Ogundare et al. 2021). However, the effect of seasonal ice melting on the surface pCO$_2$ variability has showed a rapid change from CO$_2$-rich under-ice surface water to a phytoplankton-mediated CO$_2$ sink (Chierici et al. 2004; Hoppema et al. 2007; Bakker et al. 2008).

Near the continent and in the Weddell Sea, Antarctic Bottom Water (AABW) is formed. When formed, surface-water CO$_2$ and dissolved oxygen equilibrated with atmospheric CO$_2$ and oxygen sink together with this cold and dense water to the bottom or the deep ocean (Metzl et al. 1995; Hoppema et al. 2001; Ohshima et al. 2016). In the Weddell Sea, 13–30% of AABW formation has been reported, and estimates of anthropogenic CO$_2$ in AABW showed a contribution of at least 6% of the presently estimated worldwide natural CO$_2$ sequestration in the abyssal oceans (Hoppema 2004a, b).

Due to climate change with warming and melting of sea ice and ice shelf in DML, the increased release of freshwater may increase the surface stratification, which in turn may increase the phytoplankton-mediated ocean CO$_2$ sink and seasonal pCO$_2$ variability (Chierici et al. 2004; Hoppema et al. 2007; Bakker et al. 2008). With more open water and wind-induced upwelling, surface-water pCO$_2$ will potentially increase. In the 1990s the winds were stronger over much of the SO, causing more water to be upwelled to the surface from depth (Le Quéré et al. 2007). Since these deeper waters contain higher concentrations of CO$_2$, the upwelling resulted in an anomalous release of CO$_2$ into the atmosphere, resulting in a stagnation or even a decrease in the ocean's net CO$_2$ uptake (Landschützer et al. 2015). However, in recent years, the weakening of this upwelling system enables the upper ocean to absorb more CO$_2$ (Landschützer et al. 2015), where changes in the wind-driven circulation patterns are likely responsible for higher oceanic uptake of atmospheric CO$_2$ (Takahashi et al. 2009). The current understanding of the seasonal drivers of surface-water CO$_2$ and air-sea CO$_2$ exchange in the Southern Ocean is still limited, particularly in DML, where more observations during different seasons are required to accurately represent the seasonal cycle of CO$_2$ (Lenton et al. 2013; Monteiro et al. 2015; Ogundare et al. 2021). Due to low CO$_2$ data coverage during autumn, limited sea-air CO$_2$ flux estimates from direct sea-surface CO$_2$ observations particularly in the ice-covered regions off the coast of DML and in the Weddell gyre are available.

This highlights the importance of increasing seasonal CO$_2$ observations especially during autumn/winter to improve the seasonal coverage of flux estimates in the seasonal sea ice-covered regions of DML as well as in the entire Southern Ocean. There is a general lack of coastal observations in DML, particularly in autumn and winter, when there is sea ice, which limit our understanding of the seasonal variability, biogeochemical drivers, and net ocean CO$_2$ uptake (Ogundare et al. 2021). There is a need for year-round observations on CO$_2$ system (pCO$_2$, pH, alkalinity) and other biogeochemical variables (e.g. dissolved oxygen, nutrients), as well as long-term observational efforts to better understand the changes and variability due to physical, chemical and biological processes that affect the marine environment and ecosystem in the DML region. To fill these gaps in seasonality, research expeditions in autumn and winter, the use of long-term moorings with pCO$_2$, pH and other biogeochemical sensors at different depths near the coast in DML and Argo floats (sea ice tracking) including biogeochemical sensors (Moreau et al. 2020) can increase the coverage. Moreover, during the open-water seasons, additional surface-water pCO$_2$ data can be obtained from remotely sensed data using algorithms (Mattsdotter Björk et al. 2014).

Biological system

Benthic fauna

There are very few registered biological samples from the benthos of Kong Haakon VII Hav; from early Alfred Wegener Institute cruises in the 1980s and 1990s; from one station on ANDEEP-III (2005) and from the Maud Rise seamount (Brandt et al. 2007), 15 shallow dive stations at the Japanese Syowa station (0–18 m depth) (Nakajima et al. 1982) and three benthos-stations from a Norwegian cruise in 2019 (unpub). Photo and video records of benthos from the late 1980s and onwards have been compiled by and spatially examined in 3°latitude × 3°longitude units (Gutt et al. 2013a, b). Several of these datasets are available through, for example, the SCAR Antarctic Biodiversity Portal (www.biodiversity.aq), PANGAEA (www.pangaea-de), De Broyer et al. (2011) and Teschke et al. (2020). This lack of volume in benthic datapoints (see e.g. Barnes et al. 2009) both highlights the urgent need for more benthic sampling in the area, as well as explains the use of extrapolated knowledge from neighbouring areas as a basis for understanding the Kong Haakon VII Hav benthos.

The benthic fauna can be separated in two major groups (1) the shallow- and shelf-fauna and (2) deep-sea fauna. Intuitively, the shallow and shelf-fauna is vastly more examined than that of the deep sea, despite an increased effort over the last 20 years to include areas deeper than 1000 m (De Broyer

and Koubbi 2014). The benthic fauna is generally both rich and very diverse (Clarke and Johnston 2003), but common taxa such as Brachyura (true crabs) are absent (Griffiths et al. 2014) (except from two specimens of *Hyas araneus* thought to have arrived with ballast water at South Shetland Islands (Tavares and De Melo 2004), whilst groups like pycnogonids (sea spiders) are present in exceptionally high numbers compared to other areas (Clarke and Johnston 2003; Convey et al. 2011). Geographic separation and stable environmental conditions over geological timescales have resulted in high levels of endemism (50–90% on-shelf) (Kaiser et al. 2013), with several taxa showing high percentages of crypticism and species new to science whenever they are systematically identified (up to 90% of species registered in some taxon-studies) (Brandt et al. 2011b). The benthic fauna is generally slow- and long lived, and a larger percentage than in other regions are brooders (Kaiser et al. 2013), but planktotrophy has been reported as common in the shallows (Poulin et al. 2002). Many taxa are specially adapted with *inter alia* gigantism, dwarfism and antifreeze proteins (Kaiser et al. 2013).

The shelf and shallower subtidal waters of the Antarctic are regularly disturbed by iceberg scouring and infrequently disturbed by drop-stones. This leaves a seafloor combined of both soft-bottom (mainly silty) and scouring troughs with exposed bedrock near land and smaller areas of hard-bottom where there are drop-stones. As the benthic fauna generally varies depending on available habitat or substrate, this variety of seafloor allows for diverse assemblages of fauna (Gutt and Starmans 1998; Raguá-Gil et al. 2004; Linse et al. 2013; Dorschel et al. 2014; Pineda-Metz et al. 2019). The sessile fauna is much reduced by iceberg scourings (Gerdes et al. 2003; Gutt and Piepenburg 2003) and higher in undisturbed areas, particularly in hard-bottom habitats such as drop-stones and exposed bedrock (Bathel and Gutt 1992). The silty abyssal plains are often viewed as one unbroken habitat, but geological structures such as seamounts, ridges and troughs form habitats shaping the fauna also here (Brandt et al. 2011a). The closest area to Kong Haakon VII Hav that has been extensively studied is the Weddell Sea and using this area as a theoretical template for what we can find in Kong Haakon VII Hav might be informative. Community complexity is generally high even with increasing spatial resolution, but processes driving the spatial patterns in benthos are little known (Gutt et al. 2013a). Core communities may include sessile suspension feeders, with or without sponges, supported by food entrained in strong near-bottom currents (Gutt 2007). In low-current areas, communities are typically dominated by infauna and mobile epifauna and controlled by vertical phytodetritus flux and soft sediments. For the sheltered shallow soft bottom communities, grain size of the sediment and organic content seem to be the greatest factors shaping the communities (Vause et al. 2019). For much of the fauna below 1000 m, the only pattern that

can be discerned is that depth seem to have a higher impact than latitude (Linse et al. 2007).

The shelves of the Weddell Sea are spatially highly heterogenous with regard to both biodiversity and biomass (Gutt et al. 2013a). Areas with strong near-bottom currents may hold complex communities of suspension feeders such as sponges (Barthel and Gutt 1992), soft corals, bryozoans and ascidians that may function as substrate for other invertebrates as well as hiding areas for smaller fishes. These areas can have a very high biodiversity and biomass (Gerdes et al. 1992). Areas with less strong near-bottom currents are often dominated by highly motile echinoderm taxon-groups such as Ophiuridae and Holothuriidae. Generally, the biomass of motile echinoderms will increase with a decrease in the structure-building sessile fauna and decrease when the structure builders dominate (Galéron et al. 1992).

The deep parts of the Weddell Sea, and of the Southern Ocean in general, seem to have a strong connection to other abyssal basins because of isothermal conditions in the lower water column (Brandt et al. 2007, 2011a)—especially for species with a high spreading capacity. Brooders and slow spreaders, on the other hand, seem to have very high levels of Southern Ocean endemism, and studies have shown that there are very high percentages of undescribed and cryptic species. Many case-studies show this number to be as high as 90%; this is most possibly also a sign of under-sampling (Brandt et al. 2011a).

Kong Haakon VII Hav has a very narrow available shelf and a slope marked by canyons, with the majority of the area being deeper than 1000 m. Prominent features are: seamounts (Maud Rise) and deep ridges (Astrid Ridge and Gunnerus Ridge) with adjacent deep plateaus (De Broyer et al. 2011). These structures will have coarser sediments or even for Maud Ridge some hard bottoms. First indications from the mega-benthos (video-samples) from these areas from the Norwegian cruise 2019 are that the Astrid Ridge has a high biodiversity of echinoderms and sponges, whilst Maud Rise has a high diversity of sponges, soft corals and ascidians, especially at the exposed bedrock (A.H.S Tandberg, pers. obs). Seamounts are of particular interest biologically, as they often have a unique fauna and can be viewed as "stepping stones" for distribution of benthic taxa (Pitcher et al. 2008; Kvile et al. 2014). Previous studies from Maud Rise indicate that the macro-benthos is distinctly different from the surrounding deeper plains and the deeper Weddell Sea, with several families of Polychaeta, Porifera and Isopoda being rare or seemingly endemic to the Maud Rise, and gastropods being far more abundant than in other deep Weddell Sea stations (Brandt et al. 2011a).

Studies show that the projected increase of seafloor temperature will result in an average 59% decrease of the available suitable habitats for 79% of the shelf species (Griffiths et al. 2017). The high O_2-levels supported by the steady cold

temperatures in the SO have been seen as one reason for the polar gigantism seen in many benthic species (De Broyer 1977; Chapelle and Peck 1999; Moran and Woods 2012). A warming ocean, especially warming near-bottom waters in the SO will, with its lowered capacity for O$_2$, possibly reduce not only the size of the giants (Spicer and Morley 2019), but also the general respiratory capabilities of several species and even other physiological mechanisms such as the gut-movements of pycnogonids (Woods et al. 2017). Some evidence suggests that the increase in ocean acidification will be particularly problematic for benthic calcifying animals associated with the narrow shelves of the eastern Weddell Sea (Figuerola et al. 2021), as the sediments here are shown to have high levels of CaCO$_3$ (Hauck et al. 2012).

The effect of the relatively recent trend of extended ice cover and increased amounts of ice-berg scouring and stranding in the north-eastern Weddell Sea has recently been examined (Pineda-Metz et al. 2020), where the decrease in primary (pelagic) productivity due to the increased whitening is reflected in a pronounced decrease in both microbenthic abundance and biomass.
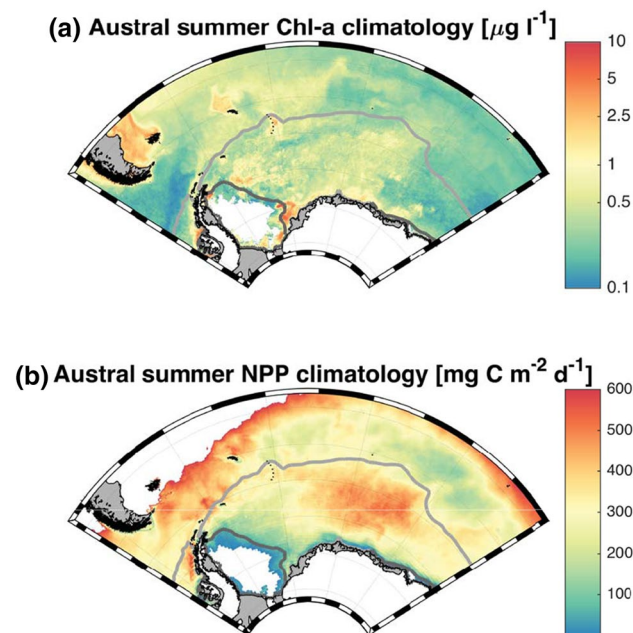

Fig. 8 Austral summer climatology (2002–2016) of satellite-derived (MODIS-Aqua) **a** sea-surface Chlorophyll-a (the main phytoplankton pigment) and **b** net phytoplankton production from the Carbon-based Production Model (CbPM, Behrenfeld et al. 2005). Both variables indicate the contribution of phytoplankton to carbon uptake and the marine food web. The mean (1987–2016) sea ice extent is indicated for September (light grey line) and February (dark grey line), obtained from NOAA/NSIDC Climate Data Record of Passive Microwave Monthly Southern Hemisphere Sea Ice Concentration

Productivity of the Dronning Maud Land sector

The DML sector does not feature any major productivity hotspots associated with the coastal or island effect common to the west Antarctic Peninsula and the sub-Antarctic islands (Blain et al. 2007; Vernet et al. 2008), but chlorophyll *a* and particularly net primary productivity derived from satellite ocean colour summer climatology (Fig. 8) reveal a large open ocean area of high phytoplankton productivity. This zones seems to be associated with topographically induced upwelling of deep waters enriched in iron by hydrothermal vent activity downstream of the Southwest Indian Ridge (Ardyna et al. 2019). In fact, a recent study suggested that primary production in open waters of the eastern part of the DML sector is responsible for the strong carbon sink of the Weddell Sea (MacGilchrist et al. 2019). The importance of this primary productivity was somehow unexpected given the relatively low overall surface ocean chlorophyll concentrations (Kauko et al. 2021) (Fig. 8). On the contrary, DML coastal polynyas such as Lutzow-Holm Bay are amongst the least productive coastal polynyas of Antarctica, based on satellite-derived ocean colour (Arrigo et al. 2015), possibly because of their small sizes and the quasi-absence of a shallow continental shelf as a sedimentary iron source. Hotspots of high primary productivity partially overlap with areas of ecological significance identified via tracking of marine predators (Hindell et al. 2020). However, there is very limited in situ data for the DML sector east of the prime meridian compared to the wealth of studies west of the prime meridian and the Weddell Gyre (Vernet et al. 2019).

Phyto- and zooplankton

Recent initiatives, including the Baseline Research on Oceanography, Krill and the Environment (BROKE and BROKE-WEST) studies (Swadling et al. 2010) or the Southern Ocean Continuous Plankton Recorder (SO-CPR) Surveys (Hosie et al. 2003; McLeod et al. 2010; Pinkerton et al. 2010b), have attempted to broaden the geographical extent of plankton studies towards the eastern Indian sector. (Hegseth and von Quillfeldt 2002). Most phytoplankton investigations are restricted to the summer months when the sea ice is at its minimum (Vernet et al. 2019) However, highest Chl-a concentrations of 3 mg m^{-3} were observed in the northeastern Weddell Sea and Lazarev Sea were observed in autumn whilst winter concentrations never exceeded 0.08 mg m^{-3} (von Harbou et al. 2011). The haptophyte algae *Phaeocystis antarctica* and diatoms (in particular *Fragilariopsis cylindrus* and *F. curta*) appear to be important phytoplankton taxa in the Weddell Gyre (Hegseth and von Quillfeldt 2002; Moreau et al. 2013) whilst autotropic dinoflagellates and cryptophytes seem to be more of local importance (Fig. 9).
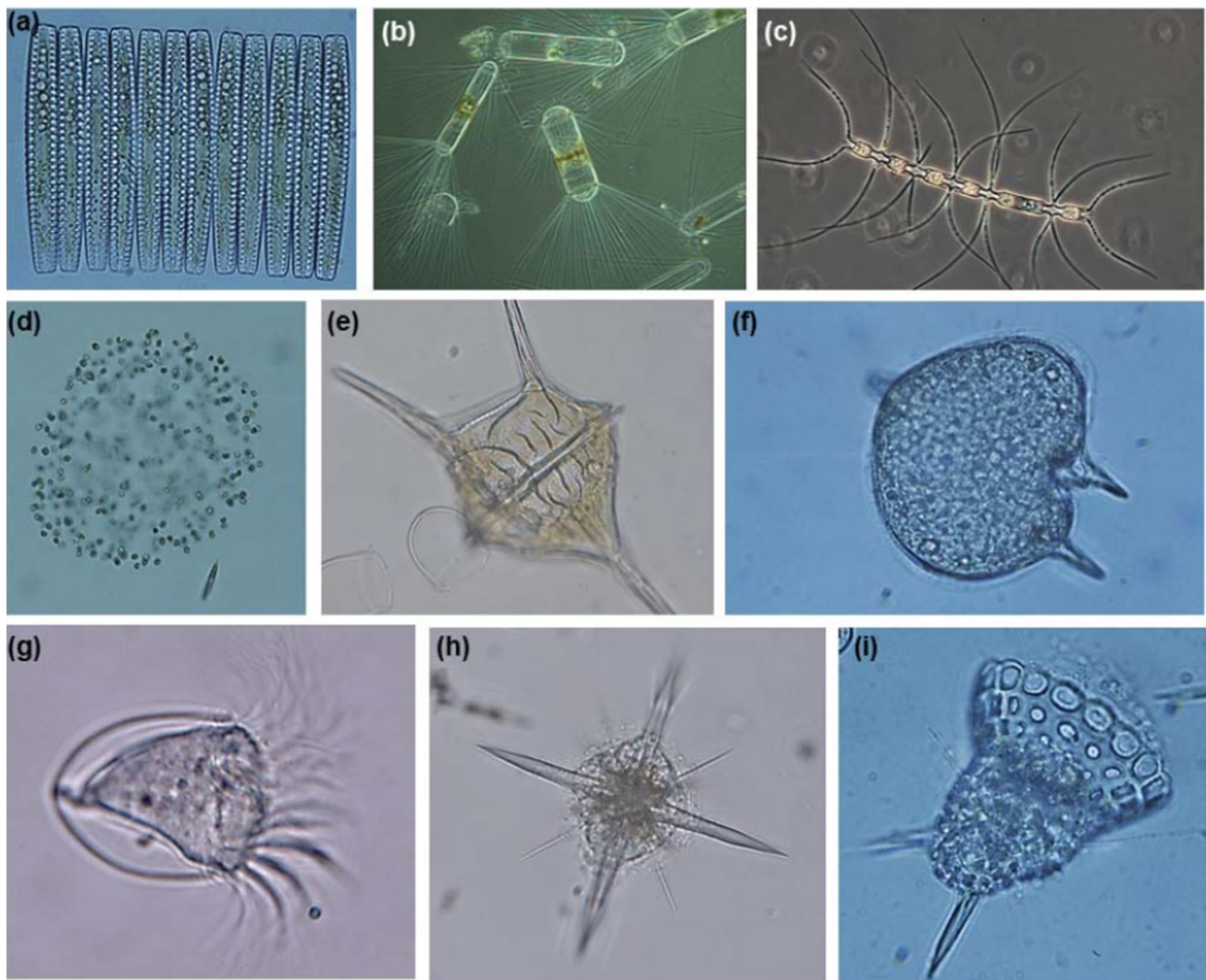
Fig. 9 Microscopic pictures of Southern Ocean protists. The diatoms **a** *Fragilariopsis kerguelensis*, **b** *Corethron pennatum* and **c** *Chaetoceros dichaeta*; the haptophyte algae **d** *Phaeocystis antarctica* (colonial form); the dinoflagellates **e** *Tripos pentagonus* and **f** *Protoperidinium* spp.; the tintinnid ciliate **g** *Acanthostomella norvegica*; unidentified Acantharia (**h**); and the radiolarian (**i**) *Cycladophora bicornis*. Protists in **a**–**e** belong to the autotrophic phytoplankton whilst those in **f**–**i** have a heterotrophic feeding mode and are categorized as protozooplankton (also referred to as microzooplankton). Light micrographs (**a**), (**f**) and (**i**) were taken by Ulrich Freier, **b** by Cecilie von Quillfeldt, **c** by Marina Montresor and (**d**), (**e**), (**g**) and (**h**) by Philipp Assmy

Protozooplankton, often referred to as microzooplankton, are important grazers of phytoplankton and usually dominated by heterotrophic flagellates, dinoflagellates and ciliates but large protozoans, including foraminifera, radiolarians and acanthareans, can make up a significant fraction of Southern Ocean protozooplankton biomass (Caron et al. 1995; Henjes et al. 2007; Decelle et al. 2012; Assmy et al. 2014). All major metazooplankton groups are represented in the Southern Ocean (Fig. 10) and total zooplankton biomass differs little between the Antarctic sectors, but latitudinally it is maximal in the Polar Frontal Zone and declines to the north and south (Atkinson et al. 2012b; Hunt et al. 2016). As in other ocean regions, copepods are the most abundant zooplankton and generally contribute the bulk of zooplankton biomass, followed by euphausiids (krill) and salps (Voronina 1998) . The hyperiid amphipod *Themisto gaudichaudii* is an important component of the zooplankton community of the northern ACC (Kane 1966) and has been shown to also extensively feed on copepods (Atkinson et al. 2012a). The abundance of copepods is typically inversely related to the abundance of krill (Atkinson et al. 1999; Priddle et al. 2003). The distributions of phyto-, proto- and metazooplankton have been recorded on transects across the frontal systems of the ACC (Froneman et al. 1995; Bathmann et al. 1997;
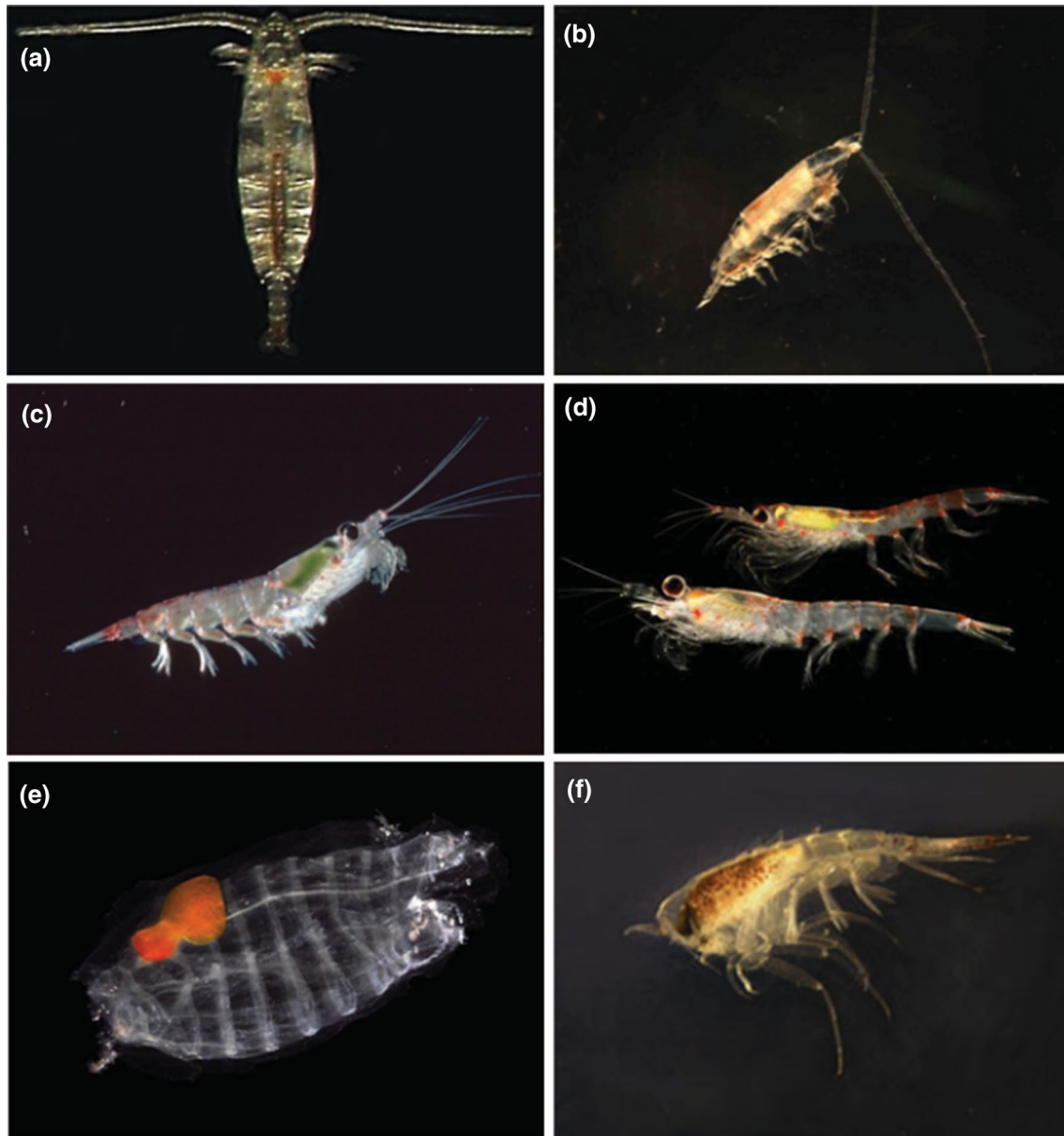
Fig. 10 Prominent Southern Ocean meso and macrozooplankton. Copepods: **a** *Calanoides acutus* (Wikipedia), **b** *Rhincalanus gigas* (Shaoqing Wang). Krill: **c** *Euphausia superba* (D.W.H. Walton), **d** *Euphausia crystallorophias* (World Register of Marine Species). Salp: **e** *Salpa thompsoni* (Jan Michels). Amphipod: **f** *Themisto gaudichaudii* (Wikipedia)

Klaas 1997, 2001; Smetacek et al. 1997, 2002; Bathmann 1998; Pakhomov et al. 2000; Froneman 2004; Pakhomov 2004; Pakhomov and Froneman 2004) , meso-zooplankton (Falk-Petersen et al. 1999; Cisewski et al. 2010) and macrozooplankton (Falk-Petersen et al. 1999; Hunt et al. 2011; Flores et al. 2014) as well as the energy content of the major zooplankton taxa (Schaafsma et al. 2018). The available phyto-, proto- and metazooplankton data cited above show a distinct dichotomy for the DML sector, with a relatively large body of information available west of the prime meridian from the Antarctic continent up to the

Polar Front, including the eastern Weddell Sea, and a striking sparseness of data east of the prime meridian.

Sea ice biota and krill

Three main types of sea ice communities can be distinguished, characterized by specific algal assemblages: surface, interior and bottom ice communities. Surface and interior sea ice communities play a relatively important role in the Southern Ocean and snow infiltration communities are a particularly important component of Antarctic

surface communities (Horner et al. 1988; Spindler 1994; Robinson et al. 1997; Garrison et al. 2003), contributing substantially to sea ice primary production (Arrigo et al. 1997). Tison et al. (2017) confirmed the importance of the infiltration layer for ice algal productivity in the Weddell Sea and the infiltration community also dominates in pack ice off DML (Kristiansen et al. 1998). *Phaeocystis antarctica* was actively growing and favoured by the growth conditions in the infiltration community (Kristiansen et al. 1998). The most ubiquitous species in the sea ice bottom layer is the pennate diatom *Fragilariopsis cylindrus* (Lim et al. 2019). The sub-ice colonial diatom *Berkeleya adéliensis* forms strands attached to the underside of sea ice. This species is mainly associated with land-fast ice in Antarctica (Riaux-Gobin et al. 2003; Belt et al. 2016). In addition, platelet ice blooms can be particularly important. These are sites of high biomass accumulation (Smetacek et al. 1992; Arrigo et al. 1995; Roukaerts et al. 2021) and have been observed both in the eastern Weddell Sea (Smetacek et al. 1992; El-Sayed 2013) and in Atka Bay near the German Antarctic station (Hoppmann et al. 2015).

A compilation of Chl *a* data (proxy of algal biomass) from Antarctic sea ice shows that the western part of the DML sector has been reasonably well covered, in particular from the eastern Weddell Sea until slightly east of the prime meridian (Meiners et al. 2012). Further east, including the entire Indian sector, only 13 ice cores were available in the circumpolar dataset (Meiners et al. 2012). Regarding ice algal and sea ice protist diversity, the record for the DML is even sparser with a few sampling locations for the eastern Weddell Sea (Van Leeuwe et al. 2018). Summer persistence of sea ice in the Weddell Gyre partly explains the higher availability of ice algal data there as compared to other regions where the sea ice retreats all the way to the continent during summer. Ice algal production might exceed phytoplankton production over the growth season in the Weddell Sea during years with extensive sea ice cover (Hegseth and von Quillfeldt 2002) when ice algal production typically contributes 10% to the overall SO primary production (Legendre et al. 1992; Arrigo et al. 1997).

Different water masses in the Southern Ocean are characterized by different euphausiid species. Most of our knowledge of euphausiid ecology is based on Antarctic krill which is by far the most important species both as a grazer and in terms of food for higher trophic levels. It is reported to feed on a wide range of food items including microplankton, copepods and other euphausiids (Atkinson et al. 2002). The distribution of Antarctic krill usually coincides with the high productive areas dominated by blooms of diatoms and *Phaeocystis*. In the pelagic realm, Antarctic krill can aggregate in massive swarms that will exert considerable local grazing pressure whilst it is more dispersed under sea ice (Smetacek et al. 1992; Tarling and Fielding 2016). Sea

ice constitutes a critical environment for the recruitment, survival and feeding of krill, in particular for juvenile stages, and ice fauna biomass is often dominated by this species (Smetacek et al. 1992; Siegel and Loeb 1995; Flores et al. 2011, 2012; Schmidt et al. 2014; Meyer et al. 2017) Antarctic krill has also been found grazing on phytodetritus on the abyssal sea floor (Schmidt et al. 2011). This versatile life strategy likely contributes to the dominance of Antarctic krill. Other important krill species include *Thysanoessa macrura* (Haraldsson and Siegel 2014) and *E. crystallorophias* (Pakhomov et al. 1998), the former of which seems to be quite widely distributed, whereas the latter is more restricted to the Antarctic Coastal Current on the narrow shelf (Boysen-Ennen and Piatkowski 1988).

Studies on Antarctic krill have been summarized across a suite of reviews (Atkinson et al. 2004; McBride et al. 2014; Hunt et al. 2016). The total krill biomass is strongly concentrated in the SW Atlantic sector (Siegel 2005; Atkinson et al. 2008). More recent efforts in the Lazarev Sea during different seasons have provided new insights into the distribution, physiology and life cycle of Antarctic krill from this area as far as 3° E (Atkinson et al. 2002; Meyer et al. 2002, 2009; Flores et al. 2011, 2012; Hunt et al. 2011; Siegel 2012; Schmidt et al. 2014). In the Lazarev Sea, two 'populations' of Antarctic krill, one in the ACC and another in the East Wind Drift, much closer to the continent, seem to reflect distinct stocks or subpopulations (Atkinson et al. 2012b). Apparently, the Lazarev Sea does not sustain a single self-maintaining population, but rather a complex transition zone of stocks from the Scotia Sea and the Cosmonaut Sea (Siegel 2012). Nevertheless, the DML sector seems to be critical for the understanding of regional krill recruitment and production (Krafft et al. 2010). Pteropods, amphipods and the arrow worm *Sagitta gazellae* are other important species of the ice-associated fauna in the Lazarev Sea (Krapp et al. 2008).

Fishes

Two distinct fish assemblages appear to characterize the SO, a coastal assemblage dominated by juvenile notothenioid fishes in many areas and an oceanic assemblage dominated by meso- and bathypelagic fishes (Kock 1992). The best-studied ocean area adjacent to DML in terms of fishes is the Lazarev Sea. Because the Coastal Current largely coincides with the shelf beak, it forms an effective physical barrier between oceanic and coastal ichthyoplankton communities in the region. This overall region is a transition zone in terms of fish fauna from the East Antarctic province, where species diversity is high and biomass low, to the West Antarctic province where species richness is lower, but biomass is higher (Wohlschlag and DeWitt 1972).

Early research cruises in the Lazarev Sea reported 25 species from eight families from collections in autumn

(Efremenko 1991). Biomass of catches of the little known benthopelagic longfin icedevil (*Aethotaxis mitopteryx*), suggest that the Lazarev Sea in an important distributional area for this species, which has slow growth rates and a concomitantly low fecundity rate (Kunzmann and Zimmermann 1992). A comparative study between the Lazarev Sea and the eastern Weddell Sea (Wöhrmann and Zimmermann 1992) reported a high percentage of non-notothenioid species in trawl catches, despite the general dominance of Nototheniidae (cod icefishes) and a patchy distribution of benthic assemblages whilst the macrourid *Macrourus holothrachys* typically dominated deep catches. Species diversity was found to be similar between the Lazarev and Weddell Seas (Ekau 1986; Gutt et al. 1994); both areas being dominated by the Nototheniidae, with slender scalyhead (*Trematomus lepidorhinus)* as the most abundant species. The Lazarev Sea showed a high number of species (*n* = 24), although with average fish abundance. The high species richness was in part due to the presence of rare species, such as emerald rockcod (*Trematomus bernacchii*) and smalleye moray cod (*Muraenolepis microps*) (Gutt et al. 1994). Myers' icefish (*Chionodraco myers*) and slender scalyhead were most abundant in benthic fish assemblages (Gutt and Ekau 1996).

Myctophid dietary preferences were determined for Antarctic lanternfish (*Electrona antarctica*) and Nichol's lanternfish (*Gymnoscopelus nicholsi*) in the Atlantic and Indian Sectors of the SO, including along the 0° Meridian from the Antarctic Polar Front to the coastline in the middle of the Lazarev Sea (Pakhomov et al. 1996). Densities were highest immediately north of the marginal ice zone, with a secondary peak in the northern vicinity of the Antarctic Polar Front. Mesozooplankton including copepods, euphausiids, hyperiid amphipods and pteropods constituted the bulk of the diet, proportional to their regional occurrences.

The top 200 m layer of the coastal and slope areas of the Lazarev Sea have previously been characterized by a diverse notothenioid larval community consisting of high densities of Antarctic silverfish (*Pleuragramma antarctica*) (Flores et al. 2008), which also dominate pelagic catches in the eastern Weddell Sea during January–February (White and Piatkowski 1993). Further offshore, diversity of the larval community decreased and was dominated by Antarctic jonasfish (*Notolepis coatsi*) and Antarctic lanternfish (Flores et al. 2008). On their easternmost transect (at 0°), Flores et al. (2008) noted that dragonfish larvae (*Bathydraco antarcticus*) became more common, potentially in response to the upwelling of deeper water layers close to the Maud Rise seamount (Holland 2001). Offshore communities did contain postlarval fishes including Antarctic deep-sea smelt *(Bathylagus antarcticus)* and a variety of lantern fishes including Brauer's lanternfish (*Gymnoscopelus braueri*), Nichol's lanternfish and Antarctic lanternfish.

Density of postlarval Antarctic lanternfish was positively related to postlarval krill abundance at 3800–4500 m (Flores et al. 2008). Juvenile Antarctic lanternfish had a diet comprised mainly of calanoid copepods, although euphausiids comprised 28% of the food items. This species as well as the Antarctic jonasfish show diurnal vertical migrations with higher densities in the epipelagic zone during dark hours (Hunt et al. 2011). Vertical migration enables them to exploit both mesopelagic and epipelagic food resources and implies that they act as an effective energy carriers between these realms. Lanternfishes thus represent a major energetic source for predators in the Lazarev Sea (Van De Putte et al. 2006).

Diets of top predators, documented on a regional basis, have provided insights into the fish community along the DML coast. In western DML, Weddell seals (*Leptonychotes weddellii*) had consumed a variety of fish species in addition to squid and krill (Plötz et al. 1986). Antarctic silverfish were most prevalent, followed by Antarctic toothfish (*Dissostichus mawsoni*), notothenoids and channichthyids. Diet varied between years, with regard to prevalence of Myers' icefish, blunt scalyhead (*Trematomus eulepidotus*), *Pagetopsis maculatas*, *Racovitzia glacialis* and long-fingered icefish (*Cryodraco antarcticus*) (Plötz et al. 1991a). Ross seals (*Ommatophoca rossii*) in the pack ice of the Kong Haakon VII Hav, north of DML had only fed on Antarctic silverfish (Skinner and Klages 1994). Antarctic petrels (*Thalassoica antarctica*) breeding at Svarthamaren may also consume fish, including Antarctic lanternfish, Antarctic silverfish, *Bathylagus* spp. and *Melamphaes* spp., but Antarctic krill numerically dominated their diet (Lorentsen et al. 1998; Descamps et al. 2016a).

Cosmonaut Sea and Cooperation Sea/Prydz Bay region mainly contained numerous Antarctic silverfish, Antarctic jonasfish and Antarctic lanternfish (Lubimova et al. 1988; Van de Putte et al. 2010). However, overall densities of fish were amongst the lowest observed in the SO, with areas to the east having an order of magnitude higher total fish densities (Hoddell et al. 2000). The coastal community in the Cosmonaut Sea showed higher species diversity than oceanic areas, containing a range of notothenioid species. Oceanic areas were relatively species poor, with Antarctic lanternfish and Antarctic jonasfish dominating in deeper water.

Two Antarctic dragonfishes in the Cosmonaut Sea and Cooperation Sea, Mawson's dragonfish (*Cygnodraco mawsoni*) and ploughfish (*Gymnodraco acuticeps*), are associated with krill swams during their early pelagic life stages (Pakhomov 1998). Mawson's dragonfish preyed on fishes (32%), with blunt scalyhead, Antarctic silverfish and longfin icedevil as the three most important species in the diet (Pakhomov 1998). Fish comprised 97% of the diet of ploughfish in the Cosmonaut Sea, with Antarctic lanternfish

and Nichol's lanternfish being the most important food items (Pakhomov 1998). Lanternfish often comprise 90% of fish preyed by seabirds, both penguins and flighted seabirds (Hopkins et al. 1993; Olsson and North 1997), as well as fish-eating marine mammals. Modelling has suggested a poleward range shift amongst sub-Antarctic lanternfishes, with increased diversity at high latitudes by mid-twenty-first century (Freer et al. 2019). Smaller, sub-Antarctic species may reach further south, which would have implications for trophic interactions. Species with restricted niches and limited available habitat will be the most vulnerable group at high latitudes because of climate warming (Freer et al. 2019). This includes the pelagic shoal species Antarctic silverfish and the icefishes, which reside on the shelf in subzero water (Mintenbeck et al. 2012).

Cephalopods

Cephalopods are widely distributed in the SO (Xavier et al. 2016), where they occupy the ecological niche of epipelagic fishes in the Antarctic Frontal Zone. They play an important role in the ecology of the SO, linking the abundant mesopelagic fish and crustaceans with higher predators such as seabirds and marine mammals (Rodhouse and White 1995; Collins and Rodhouse 2006), but are generally undersampled and poorly known. Early life stages of squid have been sampled in the Lazarev Sea during summer (seven taxa) and winter (4 taxa). (Guerrero-Kommritz 2011). The cranchiid squids *Galiteuthis glacialis* and colossal squid (*Mesonychoteuthis hamiltoni*) were both commonly caught during summer (71% of cephalopods, approximately one individual per pelagic trawl catch, $n = 129$) of and co-occurred across the sampled area. During winter, only *G. glacialis* was common (95% of cephalopods, ca. 4 per pelagic trawl catch, $n = 64$. Abundant distribution of *G. glacialis* extends into the pelagic zones of Riiser-Larsen Sea and Cosmonaut Sea (Rodhouse and Clarke 1986; Van de Putte et al. 2010). The early-life phase of *G. glacialis* is concentrated in the upper zone of the "warm deep water" beneath the Antarctic surface layer, although juveniles have also been sampled below sea ice together with adults of *Kondakovia lingimana* and *Slosarczykovia circumantarctica* (Guerrero-Kommritz 2011), species that are distributed throughout the seas around Antarctica.

Beaks of squid are often found in stomachs of albatrosses, petrels, seals and whales (Rodhouse et al. 1987, 1990; Plötz et al. 1991b; Skinner and Klages 1994). Seals feed on a variety of squid species, whereas sperm whales (*Physeter macrocephalus*) feed on the colossal squid in deep water as well as 40 smaller cephalopod species (Clarke 1980). Diets of Antarctic petrels (*Thalassioica antarctica*) breeding at Svarthamaren (250,000 pairs) contained 5% squid, mainly identified as *Psychroteuthis glacialis*, which implied

an estimated consumption of 2300 tonnes squid annually (Lorentsen et al. 1998). Food samples collected from Antarctic petrels at sea in the same study contained less crustaceans and relatively more fish and squid than those from Svarthamaren.

Seabirds

Four seabirds are common breeders in DML: the Antarctic petrel (*Thalassoica antarctica*), the snow petrel (*Pagodroma nivea*), the south polar skua (*Catharacta maccormicki*) and the emperor penguin (*Aptenodytes forsteri*) (Mehlum et al. 1988; Croxall et al. 1995; Van Franeker et al. 1999; Fretwell and Trathan 2009). Four to seven million Antarctic petrels breed in Antarctica and almost half of the known Antarctic petrel colonies are located in DML, hosting more than 60% of the breeders (Van Franeker et al. 1999). Snow petrels are less numerous and only several tens of thousands of pairs seem to breed in DML, which represents a small proportion of the entire population (Croxall et al. 1995). The world population of south polar skua is between 5000 and 8000 breeding pairs (del Hoyo et al. 1996) and the number of pairs in DML is likely, at least, in the hundreds (e.g. > 100 nests are present at Svarthamaren, Unpubl. data). There are ten emperor penguin breeding colonies uniformly distributed evenly across DML, representing approximately 16% (38,000 breeding pairs) of the breeding population (Fretwell and Trathan 2009, 2021; Fretwell et al. 2012). Adélie penguins (*Pygoscelis adeliae*) and Wilson's storm petrels (*Oceanites oceanicus*) also breed in DML but only on the very eastern coastline in the Lützow-Holm Bay area for the former (6000 adult Adélie penguins observed in summer 2004) (Kato and Ropert-Coudert 2006; Lynch and LaRue 2014) and only in very small and scattered numbers for the latter species (Ryan and Watkins 1988; Johansson and Thor 2004).

With the exception of the south polar skua that can exploit inland-breeding birds during the breeding season (Brooke et al. 1999; Busdieker et al. 2020) and then leave Antarctic waters during the winter months (Weimerskirch et al. 2015), all seabirds breeding in DML rely entirely on the marine environment including the Kong Haakon VII Hav. A large part of this marine area along the DML coastline represents an area of ecological significance (Hindell et al. 2020). Habitat use during and outside the breeding season is well described for Antarctic petrels breeding at Svarthamaren (71°53′S, 5°10′E), the largest seabird colony in Droning Maud Land. Antarctic petrels use a very large marine area during the breeding season covering the entire Kong Haakon VII Hav and the eastern part of the Weddell Sea (Fauchald and Tveraa 2006; Descamps et al. 2016b; Fauchald et al. 2017; Tarroux et al. 2020). During the non-breeding season, Antarctic petrels from Svarthamaren spend a lot of time in the same area even if the core of their distribution is shifted

westwards (Descamps et al. 2016b; Delord et al. 2020). Antarctic petrel foraging is associated with sea ice both in the breeding (Ainley et al. 1984; Fauchald et al. 2017; Tarroux et al. 2020) and non-breeding (Chapman et al. 2004; Delord et al. 2020) season. The distribution at-sea of snow petrels, emperor and Adélie penguins breeding in DML is currently unknown but observations at sea indicate that these three species, amongst many others, are common within the Kong Haakon VII Hav (Joiris et al. 2013; Ropert-Coudert et al. 2014). Overall, more than 25 seabird species have been observed in the marine area between DML and 50°S, and more than 55 species if we include observations up to 40°S (Joiris et al. 2013). This marine area is thus used by a larger seabird diversity than, for example, the Weddell Sea. The Antarctic petrel is by far the most numerous species observed south of 50°S and was especially numerous close to ice edge or in the ice pack (Joiris et al. 2013). These at-sea observations indicate that the marine environment outside DML is not only important for seabirds breeding on DML but is also used by sub-Antarctic and Antarctic seabirds breeding in other regions (Joiris et al. 2013; Ropert-Coudert et al. 2014). All these observations have been done during the summer period (breeding season) and the seabird diversity in the Kong Haakon VII Hav during the winter months remains unknown.

In general, little is known about the diet of seabirds foraging in the Kong Haakon VII Hav. The only detailed information come from the Antarctic petrel breeding at Svarthamaren (Lorentsen et al. 1998; Descamps et al. 2016a). These petrels feed mostly on Antarctic krill during the breeding season but fish also represent a significant proportion of their diet (Lorentsen et al. 1998; Descamps et al. 2016a). Stable isotopic data (Hobson and Wassenaar 1999) suggest that during the non-breeding period crustaceans (Antarctic krill) also represent an important part of Antarctic petrel diet (Descamps et al. 2016a). Emperor penguins from the eastern Weddell Sea feed mainly on several species of squid, fish, krill, amphipods and isopods (Klages 1989; Piatkowski and Pütz 1994) and we might expect that those breeding along the DML coastline have a similar varied diet. Although detailed information is lacking, some results suggest that snow petrels and Adélie penguins have also a krill-based diet (Watanuki et al. 1994). This likely indicates that the role of Antarctic krill in the marine ecosystem in the Kong Haakon VII Hav might be central and similar to the one played in the Weddell Sea (Rau et al. 1992; Hodum and Hobson 2000).

Except for Antarctic petrels, the current status and trends of most seabird species breeding in DML or using the marine area outside DML remains largely unknown. Data from the longest-studied population of emperor penguins at Terre Adélie coupled with future levels of sea ice variability modelled under various climate change scenarios demonstrated that not only is the demographic trajectory of the species highly dependent upon variability in sea ice, but that the DML coastline is predicted to be the region most likely to experience the greatest levels of sea ice variability into the future (Jenouvrier et al. 2014). Despite this apparent threat, there are no available data on emperor penguin populations in DML and their current trend is unknown. Generally, information is lacking for virtually all seabird species breeding in DML, except for the Antarctic petrel. Long-term monitoring data from Antarctic petrels at Svarthamaren exist since 1996 and indicate that the population is currently declining (Descamps et al. 2016b). The population dynamics of the Antarctic petrel is partly explained by fluctuations in the Southern Oscillation Index (SOI) and Antarctic Oscillation (AAO) (Descamps et al. 2016b) and by extreme weather events {Citation}. The mechanisms linking changes in AAO or SOI to changes in Antarctic petrel population are currently unknown but may involve changes in primary productivity and prey availability. The ongoing decline in Antarctic petrel at Svarthamaren may thus reflect large-scale changes in their main prey, i.e. Antarctic krill (Atkinson et al. 2004). Considering the central role of Antarctic krill in the marine ecosystem and in the diet of many seabird species, such a decline would suggest that most seabirds breeding in DML or using the Kong Haakon VII Hav are at risk. Important Bird and Biodiversity Areas (IBAs) have been identified around the Antarctic continent, including DML, and their overlap compared with the currently adopted and proposed network of key management areas (Handley et al. 2021).

Marine mammals

Pinnipeds

Four pinniped species breed on ice in coastal areas along DML: crabeater (*Lobodon carcinophagus*); Weddell (*Leptonychotes weddellii*); Ross (*Ommatophoca rossi*); and leopard (*Hydrurga leptonyx*) seals. Weddell seals use shore-fast ice, and their general ecology is well documented from other regions. Abundance or densities of seals are estimated for the DML area, covering parts of the area, but most of these are based on data collected decades ago (Hall-Martin 1974; Southwell et al. 2012). The most comprehensive survey for the DML region was conducted as part of the Antarctic Pack Ice Seal (APIS) programme; APIS covered most coastal areas in DML, surveying seals over five austral summers between 1996 and 2001 (Gurarie et al. 2017). The modelled abundance in the surveyed area (from 30°W to 10°E) was estimated to be 514 (95% CI 337–886) $\times 10^3$ crabeater seals, 60 (95% CI 43.2–94.4) $\times 10^3$ Weddell seals and 13.2 (9% CI 5.50–39.7) $\times 10^3$ leopard seals. Crabeater seal estimated densities in this area were similar to those obtained during surveys in the Pacific and Indian Ocean sectors under

APIS. Few Ross seals were observed ($n = 24$), leading to a conservative estimate of 830 (95% CI 119–2894) individuals over the study area. In a more recent ship-based survey in 2015/2016 in the eastern Weddell Sea, including areas off DML, crabeater seals were again found to be the dominant species (Bester et al. 2019) Interestingly, in this same study Ross seals were found to be relatively abundant off the Princess Martha Coast (0.77 seals nm^{-2}) and they also occurred in relatively high numbers in the eastern Weddell Sea (Bester et al. 2020).

Dietary information for seals from DML is only available for small parts of this vast area and again these data are decades old. Stomach contents from Weddell seals revealed that fish, cephalopods and krill were the most important prey for this species (Plötz et al. 1986, 1991a). A study of stomach contents of Ross seals collected from Kong Haakon VII Hav ($n = 40$) found that the Antarctic silverfish and the glacial squid *P. glacialis* were dominant prey items (Skinner and Klages 1994).

Biologging studies exist on the behaviours of seals from the DML area, though most published work is based on data in some cases that are over twenty years old. Studies conducted on crabeater seals suggest they spend most of their time in the drift ice, diving shallowly in a diel pattern that suggests that they target krill (Nordøy et al. 1995) . Weddell seals appear to have a bimodal feeding pattern, foraging either near the surface or benthically, often near shelf edges (Nordøy et al. 1995; Bornemann et al. 1998; Plötz et al. 2002; Watanabe et al. 2006; Liebsch et al. 2007; McIntyre et al. 2013; Boehme et al. 2016). Ross seals spend most of their time in drift ice or near the Antarctic polar front where they feed pelagically (Blix and Nordøy 2007). Leopard seal diving behaviour in the region is similar to that reported elsewhere with them diving to shallow depths, usually near the edges of drift ice, where they hunt at or near the surface (Nordøy and Blix 2009). Southern elephant seals (*Mirounga leonina*) from subantarctic breeding grounds such as Bouvetøya, Prince Edward Islands and Kerguelen Island conduct overwintering foraging trips to the ice shelf in DML, suggesting that the region has enough secondary production to support upper trophic predators (Biuw et al. 2010; Mcintyre et al. 2012; Labrousse et al. 2015). Moored passive acoustic monitoring devices have also been used to examine vocal repertoires of all four seals species in DML, characterizing the temporal occurrence and species composition at various sites along the coastline (Terhune et al. 2008; Van Opzeeland et al. 2010; Van Opzeeland and Hillebrand 2020).

Cetaceans

Cetaceans data are scarce throughout the DML area, although limited minke whales (*Balaenoptera acutorostrata*)

observational data exist (Plötz et al. 1991b) as well as density estimates (Kasamatsu et al. 1998; Williams et al. 2014) and acoustic presence data (Reeves et al. 1996; Shabangu et al. 2020; Van Opzeeland and Hillebrand 2020). The status of sperm whales (*Physeter macrocephalus*), beaked whales (mainly southern bottlenose whales (*Hyperoodon planifrons*)) and killer whales (*Orcinus orca*) in areas off the DML coast is presented in (Kasamatsu 1995), but these data are now close to three decades old. Branch et al. (2007) review present (and past) densities and distributions of blue whales (*Balaenoptera musculus*) from the Southern Hemisphere including DML, where this species appears to be increasing in abundance. Surveys along the coast off DML using icebreaker supported helicopters in the summers of 2006/07 and 2008/09 (Scheidat et al. 2011) registered four species of whales along the Larsen Ice Shelf, including the Antarctic minke whale, Arnoux's beaked whale (*Berardius arnuxii*), southern bottlenose whale (*Hyperoodon planifrons*) and killer whales.

Habitat modelling efforts, based on opportunistic sightings of humpback (*Megaptera novaeangliae*) and minke whales in the DML region from the period 2005–2011 provide some information that is potentially useful for survey planning (Bombosch et al. 2014). Generally, suitable humpback whale habitat exists in all ice-free areas north of the ice edge, whilst minke whale habitat includes sea ice-covered areas in addition. Passive acoustics have revealed that many species including blue, fin (*Balaenoptera physalus*), humpback, and minke whales are present in DML throughout the year (Thomisch et al. 2016; Menze et al. 2017; Schall et al. 2020; Van Opzeeland and Hillebrand 2020).

Larger-scale habitat suitability modelling efforts have, in general, identified the coast of DML as a hotspot for many upper trophic species including humpback whales, crabeater seals and Weddell seals (Hindell et al. 2020).

Pollution

Persistent organic pollutants (POPs) have been detected in sea water, sea ice, and air from DML, the levels are low in the few available studies (Kallenborn et al. 2013). A suite of POPs have been analysed in ice algae, phytoplankton, zooplankton, krill and Antarctic lanternfish from DML (Bengtson Nash et al. 2008; Hallanger et al. 2011). The polybrominated diphenyl ethers (PBDEs) levels in Antarctic krill are comparable to *Thyssanoessa inermis* sampled from the Svalbard area, as well as two other studies in the Antarctic region (Chiuchiolo et al. 2004; Corsolini et al. 2006). Of the seabirds from DML and its immediate surrounds, the south polar skua from Svarthammaren and Adélie penguins from Syowa station have been analysed for POPS, having lower levels than similar trophic levels seabirds in the Northern Hemisphere (Bustnes et al. 2006; Yamashita

et al. 2018). Other seabirds from Vestfjella and Bouvetøya also contained POPs (Norheim et al. 1982). Perfluorinated compounds (PFCs) has been analysed, but not detected, in krill both west and east of eastern border of DML (Bengtson Nash et al. 2010).

Information on pinniped ecotoxicology, health and disease studies are limited to studies conducted decades ago (Steinhagen-Schneider 1986; Schumacher et al. 1992; Stenvers et al. 1992; Vetter et al. 1997, 2003; Vetter and Luckas 2000; Tryland et al. 2005, 2012). Levels of several metals, toxaphenes and organochlorines are high and some of the seals have been exposed to phocine herpesvirus, Brucella, toxoplasma and parapox.

Mercury has been detected in air from research station Troll since 2007 (Pfaffhuber et al. 2012; Pernilla Bohlin-Nizzetto, NILU, pers. comm.). Mercury has also been detected in samples of snow in a transect from Dome Fuji to Syowa (Han et al. 2011). Mercury and other metals have been detected in Antarctic petrel and south polar skua from DML and Bouvetøya (Norheim et al. 1982; Nygård et al. 2001; Carravieri et al. 2018).

Macroplastics has been observed visually in the northern part of DML at a density of 0.2 items km^{-2} (Eriksen et al. 2014). Though microplastic particles or fibres have not yet been detected (Kuklinski et al. 2019).

Discussion

The seascape abutting DML is clearly polarized in terms of the availability of scientific knowledge, with a clear lack of data in its eastern part. The geographical biases in availability of data are likely related to the research effort dedicated by national Antarctic programmes or the lack thereof. For example, South Africa has had research expeditions to Antarctica since 1959 on an almost annual basis, as has Germany since 1979, with both countries running year-round Antarctic stations in western DML. These regular research expeditions have generated considerable amounts of information, and importantly, time series of environmental variables throughout western DML and the eastern Weddell Sea. To the east of this longitude, none of the five nations which possess either permanent or seasonal research stations (Belgium, India, Japan, Norway and Russia) have had an icebreaking research vessel dedicated to regular Antarctic research; this has limited the capacity to collect scientific data throughout the eastern region.

Some of the knowledge gaps identified in DML are systemic to Antarctica; for example, an appropriate understanding of atmosphere/ocean carbon flux is lacking, as is the ability to characterize contemporary levels of pollution outside the immediate vicinity of Antarctic stations that have a year-round presence. Similarly, knowledge on ice shelf dynamics is poor, with a better understanding required to understand the different sensitivities of individual ice shelves to climactic and oceanic forcing. Additionally, the distribution of paleoceanographic data beyond instrument records from the SO is currently too sparse to infer the complicated structure of climate dynamics and the range of past natural climate change.

Currently, across the coastal marine environment off DML, there is neither a targeted satellite monitoring programme nor field surveys of ice shelves to quantify patterns of basal melting, runoff and subsequent drainage, all of which can drive the disintegration of ice shelves. There is a paucity of oceanographic data available under ice shelves, with the exception of Fimbulisen and a need to further our understanding of the slope front dynamics along the shelf break of DML. In the context of ice shelf dynamics and coastal ocean processes, there is a clear lack of data in the sea ice-covered coastal waters of Antarctica, though development of under-ice mooring systems and use of animal-borne oceanographic sensors have proved valuable. Indeed, the information on interactions between sea ice and coastal oceanography throughout the eastern region of DML are limited to satellite data, modelling efforts, Argo floats and limited amounts of animal-borne, sensor data.

Bathymetry plays a key role in directing coastal ocean currents, with intrusions of warm water masses such as the Warm Deep Water onto the shelf being facilitated by canyons and channels punctuated along the shelf break. However, appropriately resolved swath mapping makes up only a small part of contemporary bathymetry data sets, particularly along eastern DML and bathymetry under ice shelves is little known. Thus, the ability to predict the future of ice shelves is hampered by an absence of glaciological, oceanographic and geological data throughout eastern DML, with only the combined study of these fields providing appropriate information.

Biological aspects of ecosystem function in terms of temporally relevant data can best be described as almost non-existent, with the exception of satellite-derived ocean colour that has provided valuable information on phytoplankton biomass and productivity since the SeaWiFS was launched in 1997. Mapping Vulnerable Marine Ecosystems (VME) is fundamental to regulating their protection; CCAMLR has specific Conservation Measures directed to this issue. However, even basic mapping of species at different trophic levels is lacking east of the prime meridian, whilst to its west data on benthic communities are limited to sparse collections of photo images and a few other studies. Knowledge on the lower trophic food web (e.g. plankton and krill) and fish assemblages is rudimentary, precluding predictions on future trends with potential new stressors. Indeed, currently, the best available scientific knowledge of the lower trophic food web is largely limited to inferences of what might be

present, based on geomorphological and oceanographic similarities with other regions of Antarctica for which data exists. This severely limits our understanding of contemporary and future ecosystem functioning and how these may be impacted by climate change.

At higher trophic levels (seabirds, seals and whales), only the Antarctic petrel colony at Svarthamaren has received any form of long-term attention. However, whilst data from this colony have been used to characterize population trends and indicate that the DML marine environment is experiencing large-scale changes, information on the lower trophic levels (particularly in terms of prey distribution and composition) has hampered efforts to understand what drives these trends. Importantly, almost all data are from the summer season; information outside this seasonal period is essential to place summer population trends into context. Even basic information across DML on emperor penguin ecology such as the breeding schedule is largely non-existent. Satellite-derived estimates of breeding population sizes have been inferred from faecal stains on snow, though these have yet to be ground-truthed such that colony size can be determined with any certainty. Data are lacking on the critical at-sea foraging habitat of breeding adults. The South African National Antarctic Programme is currently using data from tagged juveniles birds to determine habitat exploitation of post-fledging chicks. For Adélie penguins, simple presence-absence data are limited either to Soviet-era ship-based counts, or through satellite image analysis which suggests this species is absent from the entirety of DML, although recent tagging of non-breeding Adélie penguins outside the South African Antarctic station suggests they utilize this region. The only data available on seal abundance and distribution east of the prime meridian are from two surveys conducted between 1996 and 2001, though at-sea sightings data from both the South African and German research vessels are abundant to the west of this longitude. Similarly, knowledge of cetacean abundance and distribution to the east of the prime meridian is limited to surveys conducted almost three decades ago.

The disparity between western and eastern DML in terms of data availability is clear, and presumably linked to the historical capacity of nations to conduct marine research in the region. The lack of basic data on fundamental aspects of the physical, geological and biological nature of eastern DML make predictions of future trends difficult to impossible. In turn, the capacity to provide management advice at either a national or international level (sensu ATCM or CCAMLR) in the context of ecosystem responses to changes in climate patterns is limited to modelled responses from incomplete data, or data extrapolated from other regions of the Antarctic ecosystem that may or may not resemble DML. Modelling of available data is one avenue of potential knowledge

advancement and at least an appropriate way to develop hypotheses for empirical testing which in turn can help prioritize data collection. However, addressing the linked issues of poor data coverage and poor or inappropriate modelling exercises requires a commitment over timescales of years and without this commitment, achieving even a basic understanding of the region will be challenging. Importantly, increased employment of new technology to facilitate mapping and monitoring must also be considered in tandem with field-based empirical research to ensure adequate data collection for improved regional model forecasting. Clearly, a directed programme of research is required to generate the necessary data; this will require a coordinated approach and a commitment over timescales of years in order to achieve.

Author contributions ADL wrote the introduction, discussion and edited the manuscript sections. CVQ managed and collated the author contributions to each section. All other authors contributed to writing the manuscript sections and editing the final draft.

Declarations

Competing interests No authors have competing interests.

Research involving human and animal rights No animals were used in the preparation of this review.

Consent to participate No human studies were conducted, thus no consents were required in the preparation of this review.

References

Adusumilli S, Fricker HA, Medley B et al (2020) Interannual variations in meltwater input to the Southern Ocean from Antarctic

ice shelves. Nat Geosci 13:616–620. https://doi.org/10.1038/s41561-020-0616-z

Ainley DG, O'Connor EF, Boekelheide RJ (1984) The marine ecology of birds in the Ross Sea, Antarctica. Ornithol Monogr 32:iii–97. https://doi.org/10.2307/40166773

Allan RJ, Gergis J, D'Arrigo RD (2020) Placing the AD 2014–2016 'protracted' El Niño episode into a long-term context. Holocene 30:90–105. https://doi.org/10.1177/0959683619875788

Allen CS, Pike J, Pudsey CJ (2011) Last glacial-interglacial sea-ice cover in the SW Atlantic and its potential role in global deglaciation. Quat Sci Rev 30:2446–2458. https://doi.org/10.1016/j.quascirev.2011.04.002

Alley KE, Scambos TA, Miller JZ et al (2018) Quantifying vulnerability of Antarctic ice shelves to hydrofracture using microwave scattering properties. Remote Sens Environ 210:297–306. https://doi.org/10.1016/j.rse.2018.03.025

Altnau S, Schlosser E, Isaksson E, Divine D (2015) Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica. Cryosphere 9:925–944. https://doi.org/10.5194/tc-9-925-2015

Ansorge IJ, Jackson JM, Reid K et al (2015) Evidence of a southward eddy corridor in the South-West Indian ocean. Deep-Sea Res Part II 119:69–76. https://doi.org/10.1016/j.dsr2.2014.05.012

Aoki S (2017) Breakup of land-fast sea ice in Lützow-Holm Bay, East Antarctica, and its teleconnection to tropical Pacific sea surface temperatures. Geophys Res Lett 44:3219–3227. https://doi.org/10.1002/2017GL072835

Ardyna M, Lacour L, Sergi S et al (2019) Hydrothermal vents trigger massive phytoplankton blooms in the Southern Ocean. Nat Commun. https://doi.org/10.1038/s41467-019-09973-6

Armour KC, Marshall J, Scott JR et al (2016) Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. Nat Geosci 9:549–554. https://doi.org/10.1038/ngeo2731

Arndt JE, Schenke HW, Jakobsson M et al (2013) The international bathymetric chart of the Southern Ocean (IBCSO) version 1.0-A new bathymetric compilation covering circum-Antarctic waters. Geophys Res Lett 40:3111–3117. https://doi.org/10.1002/grl.50413

Arndt S, Hoppmann M, Schmithüsen H et al (2020) Seasonal and interannual variability of landfast sea ice in Atka Bay, Weddell Sea, Antarctica. Cryosphere Discuss 2020:1–26. https://doi.org/10.5194/tc-2019-293

Arrigo KR, Dieckmann G, Gosselin M et al (1995) High resolution study of the platelet ice ecosystem in McMurdo Sound, Antarctica: biomass, nutrient, and production profiles within a dense microalgal bloom. Mar Ecol Prog Ser 127:255–268. https://doi.org/10.3354/meps127255

Arrigo KR, Worthen DL, Lizotte MP et al (1997) Primary production in Antarctic sea ice. Science 276:394–397. https://doi.org/10.1126/science.276.5311.394

Arrigo KR, van Dijken GL, Bushinsky S (2008) Primary production in the Southern Ocean, 1997–2006. J Geophys Res 113:C08004. https://doi.org/10.1029/2007JC004551

Arrigo KR, Van Dijken GL, Strong AL (2015) Environmental controls of marine productivity hot spots around Antarctica. J Geophys Res 120:5545–5565. https://doi.org/10.1002/2015JC010888

Assmy P, Cisewski B, Henjes J et al (2014) Response of the proto-zooplankton assemblage during the European Iron Fertilization Experiment (EIFEX) in the Antarctic circumpolar current. J Plankton Res 36:1175–1189. https://doi.org/10.1093/plankt/fbu068

Atkinson A, Ward P, Hill A et al (1999) Krill-copepod interactions at South Georgia, Antarctica, II. *Euphausia superba* as a major control on copepod abundance. Mar Ecol Prog Ser 176:63–79. https://doi.org/10.3354/meps176063

Atkinson A, Meyer B, Stübing D et al (2002) Feeding and energy budgets of Antarctic krill *Euphausia superba* at the onset of winter - II Juveniles and adults. Limnol Oceanogr 47:953–966. https://doi.org/10.4319/lo.2002.47.4.0953

Atkinson A, Siegel V, Pakhomov E, Rothery P (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432:100–103. https://doi.org/10.1038/nature02996

Atkinson A, Siegel V, Pakhomov EA et al (2008) Oceanic circumpolar habitats of Antarctic krill. Mar Ecol Prog Ser 362:1–23. https://doi.org/10.3354/meps07498

Atkinson A, Nicol S, Kawaguchi S et al (2012a) Fitting *Euphausia superba* into Southern Ocean food-web models: a review of data sources and their limitations. CCAMLR Sci 19:219–245

Atkinson A, Ward P, Hunt BPV et al (2012b) An overview of Southern Ocean zooplankton data: abundance, biomass, feeding and functional relationships. CCAMLR Sci 19:171–218

Auger M, Morrow R, Kestenare E et al (2021) Southern Ocean in-situ temperature trends over 25 years emerge from interannual variability. Nat Commun 12:514. https://doi.org/10.1038/s41467-020-20781-1

Bakker DCE, De Baar HJW, Bathmann UV (1997) Changes of carbon dioxide in surface waters during spring in the Southern Ocean. Deep-Sea Res Part II 44:91–127. https://doi.org/10.1016/S0967-0645(96)00075-6

Bakker DCE, Hoppema M, Schröder M et al (2008) A rapid transition from ice covered CO_2 rich waters to a biologically mediated CO_2 sink in the eastern Weddell Gyre. Biogeosciences 5:1373–1386. https://doi.org/10.5194/bg-5-1373-2008

Barnes M (2015) Aichi targets: protect biodiversity, not just area. Nature 526:195

Barnes DKA, Griffiths HJ, Kaiser S (2009) Geographic range shift responses to climate change by Antarctic benthos: Where we should look. Mar Ecol Prog Ser 393:13–26. https://doi.org/10.3354/meps08246

Barthel D, Gutt J (1992) Sponge associations in the eastern Weddell Sea. Antarct Sci 4:137–150. https://doi.org/10.1017/S0954102092000221

Bathmann UV (1998) Ecology and biogeochemistry in the Atlantic sector of the southern ocean during Austral spring: the first JGOFS expedition aboard RV "Polarstern." J Mar Syst 17:77–85

Bathmann UV, Scharek R, Klaas C et al (1997) Spring development of phytoplankton biomass and composition in major water masses of the Atlantic sector of the Southern Ocean. Deep-Sea Res Part II 44:51–67. https://doi.org/10.1016/S0967-0645(96)00063-X

Behrenfeld MJ, Boss E, Siegel DA, Shea DM (2005) Carbon-based ocean productivity and phytoplankton physiology from space. Glob Biogeochem Cycles. https://doi.org/10.1029/2004GB002299

Bell RE, Banwell AF, Trusel LD, Kingslake J (2018) Antarctic surface hydrology and impacts on ice-sheet mass balance. Nat Clim Change 8:1044–1052. https://doi.org/10.1038/s41558-018-0326-3

Belt ST, Smik L, Brown TA et al (2016) Source identification and distribution reveals the potential of the geochemical Antarctic sea ice proxy IPSO25. Nat Commun. https://doi.org/10.1038/ncomms12655

Bengtson Nash SM, Poulsen AH, Kawaguchi S et al (2008) Persistent organohalogen contaminant burdens in Antarctic krill (*Euphausia superba*) from the eastern Antarctic sector: a baseline study. Sci Total Environ 407:304–314. https://doi.org/10.1016/j.scitotenv.2008.08.034

Bengtson Nash S, Rintoul SR, Kawaguchi S et al (2010) Perfluorinated compounds in the Antarctic region: ocean circulation provides

prolonged protection from distant sources. Environ Pollut 158:2985–2991. https://doi.org/10.1016/j.envpol.2010.05.024

Berger S, Drews R, Helm V et al (2017) Detecting high spatial variability of ice shelf basal mass balance, Roi Baudouin Ice Shelf, Antarctica. Cryosphere 11:2675–2690. https://doi.org/10.5194/tc-11-2675-2017

Bester MN, Wege M, Lübcker N et al (2019) Opportunistic ship-based census of pack ice seals in eastern Weddell Sea, Antarctica. Polar Biol 42:225–229. https://doi.org/10.1007/s00300-018-2401-7

Bester MN, Wege M, Oosthuizen WC, Bornemann H (2020) Ross seal distribution in the Weddell Sea: fact and fallacy. Polar Biol 43:35–41. https://doi.org/10.1007/s00300-019-02610-4

Bianchi C, Gersonde R (2004) Climate evolution at the last deglaciation: the role of the Southern Ocean. Earth Planet Sci Lett 228:407–424. https://doi.org/10.1016/j.epsl.2004.10.003

Bindschadler R, Vornberger P, Fleming A, Fox A, Mullins J, Binnie D, Gorodetzky D (2008) The Landsat image mosaic of Antarctica. Remote Sens Environ 112(12):4214–4226

Biuw M, Nøst OA, Stien A et al (2010) Effects of hydrographic variability on the spatial, seasonal and diel diving patterns of Southern Elephant seals in the Eastern Weddell sea. PLoS ONE 5:e13816

Blain S, Quéguiner B, Armand L et al (2007) Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature 446:1070–1074. https://doi.org/10.1038/nature05700

Blix AS, Nordøy ES (2007) Ross seal (Ommatophoca rossii) annual distribution, diving behavior, breeding and moulting, off Queen Maud Land, Antarctica. Polar Biol 31:1449–1458. https://doi.org/10.1007/s00300-007-0306-y

Boehme L, Baker A, Fedak M et al (2016) Bimodal winter haul-out patterns of adult Weddell seals (Leptonychotes weddellii) in the southern Weddell Sea. PLoS ONE. https://doi.org/10.1371/journal.pone.0155817

Boening C, Lebsock M, Landerer F, Stephens G (2012) Snowfall-driven mass change on the East Antarctic ice sheet. Geophys Res Lett. https://doi.org/10.1029/2012GL053316

Bombosch A, Zitterbart DP, Van Opzeeland I et al (2014) Predictive habitat modelling of humpback (Megaptera novaeangliae) and Antarctic minke (Balaenoptera bonaerensis) whales in the Southern Ocean as a planning tool for seismic surveys. Deep Sea Res Part 1 Oceanogr Res Pap 91:101–114. https://doi.org/10.1016/j.dsr.2014.05.017

Bornemann H, Mohr E, Ploetz J et al (1998) The tide as zeitgeber for Weddell seals. Polar Biol 20:396–403. https://doi.org/10.1007/s003000050320

Borstad C, McGrath D, Pope A (2017) Fracture propagation and stability of ice shelves governed by ice shelf heterogeneity. Geophys Res Lett 44:4186–4194. https://doi.org/10.1002/2017GL072648

Boysen-Ennen E, Piatkowski U (1988) Meso- and macrozooplankton communities in the Weddell Sea, Antarctica. Polar Biol 9:17–35. https://doi.org/10.1007/BF00441761

Branch TA, Matsuoka K, Miyashita T (2004) Evidence for increases in Antarctic blue whales based on Bayesian modelling. Mar Mamm Sci 20:726–754. https://doi.org/10.1111/j.1748-7692.2004.tb01190.x

Branch TA, Stafford KM, Palacios DM et al (2007) Past and present distribution, densities and movements of blue whales Balaenoptera musculus in the Southern Hemisphere and northern Indian Ocean. Mammal Rev 37:116–175. https://doi.org/10.1111/j.1365-2907.2007.00106.x

Brandt A, Ebbe B, Gooday AJ (2007) Introduction to ANDEEP, summary and outlook. Deep-Sea Res Part II 54:1645–1651. https://doi.org/10.1016/j.dsr2.2007.07.001

Brandt A, Bathmann U, Brix S et al (2011a) Maud Rise: a snapshot through the water column. Deep-Sea Res Part II 58:1962–1982

Brandt A, Bathmann U, Brix S et al (2011b) Maud Rise: a snapshot through the water column. Deep-Sea Res Part II 58:1962–1982. https://doi.org/10.1016/j.dsr2.2011.01.008

Brooke MDL, Keith D, Røv N (1999) Exploitation of inland-breeding Antarctic petrels by south polar skuas. Oecologia 121:25–31. https://doi.org/10.1007/s004420050903

Brooks CM, Crowder LB, Österblom H, Strong AL (2020) Reaching consensus for conserving the global commons: the case of the Ross Sea Antarctica. Conserv Lett 13:e12676

De Broyer C, Koubbi P, Stoddart M (2014) Biogeographic atlas of the Southern Ocean. Census of Antarctic marine life, pp 2–6

Busdieker KM, Patrick SC, Trevail AM, Descamps S (2020) Prey density affects predator foraging strategy in an Antarctic ecosystem. Ecol Evol 10:350–359. https://doi.org/10.1002/ece3.5899

Bustnes JO, Tveraa T, Henden JA et al (2006) Organochlorines in Antarctic and Arctic avian top predators: a comparison between the south polar skua and two species of northern hemisphere gulls. Environ Sci Technol 40:2826–2831. https://doi.org/10.1021/es051920q

Campbell EC, Wilson EA, Moore GWK et al (2019) Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. Nature 570:319–325. https://doi.org/10.1038/s41586-019-1294-0

Caron DA, Michaels AF, Swanberg NR, Howse FA (1995) Primary productivity by symbiont-bearing planktonic sarcodines (Acantharia, Radiolaria, Foraminifera) in surface waters near Bermuda. J Plankton Res 17:103–129. https://doi.org/10.1093/plankt/17.1.103

Carravieri A, Fort J, Tarroux A et al (2018) Mercury exposure and short-term consequences on physiology and reproduction in Antarctic petrels. Environ Pollut 237:824–831. https://doi.org/10.1016/j.envpol.2017.11.004

Chapelle G, Peck LS (1999) Polar gigantism dictated by oxygen availability. Nature 398:114–115. https://doi.org/10.1038/20099

Chapman EW, Ribic CA, Fraser WR (2004) The distribution of seabirds and pinnipeds in Marguerite Bay and their relationship to physical features during austral winter 2001. Deep-Sea Res Part II 51:2261–2278

Chavanne CP, Heywood KJ, Nicholls KW, Fer I (2010) Observations of the Antarctic Slope undercurrent in the Southeastern Weddell Sea. Geophys Res Lett. https://doi.org/10.1029/2010GL043603

Chierici M, Fransson A, Turner DR et al (2004) Variability in pH, fCO$_2$, oxygen and flux of CO$_2$ in the surface water along a transect in the Atlantic sector of the Southern Ocean. Deep-Sea Res Part II 51:2773–2787. https://doi.org/10.1016/j.dsr2.2001.03.002

Chiuchiolo AL, Dickhut RM, Cochran MA, Ducklow HW (2004) Persistent organic pollutants at the base of the Antarctic marine food web. Environ Sci Technol 38:3551–3557. https://doi.org/10.1021/es0351793

Chown SL, Brooks CM, Terauds A et al (2017) Antarctica and the strategic plan for biodiversity. PLoS Biol. https://doi.org/10.1371/journal.pbio.2001656

Cisewski B, Strass VH, Rhein M, Krägefsky S (2010) Seasonal variation of diel vertical migration of zooplankton from ADCP backscatter time series data in the Lazarev Sea, Antarctica. Deep Sea Res Part 1 Oceanogr Res Pap 57:78–94. https://doi.org/10.1016/j.dsr.2009.10.005

Clark PU, Archer D, Pollard D et al (2006) The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO$_2$. Quat Sci Rev 25:3150–3184. https://doi.org/10.1016/j.quascirev.2006.07.008

Clarke MR (1980) Cephalopods in the diet of sperm whales. Discov Rep 37:56–64

Clarke A, Johnston NM (2003) Antarctic marine benthic diversity. Oceanogr Mar Biol Annu Rev 41:47–114

Collins MA, Rodhouse PGK (2006) Southern ocean cephalopods. Adv Mar Biol 50:191–265

Collins LG, Allen CS, Pike J et al (2013) Evaluating highly branched isoprenoid (HBI) biomarkers as a novel Antarctic sea-ice proxy in deep ocean glacial age sediments. Quat Sci Rev 79:87–98. https://doi.org/10.1016/j.quascirev.2013.02.004

Constable AJ, Costa DP, Schofield O et al (2016) Developing priority variables ("ecosystem Essential Ocean Variables" - eEOVs) for observing dynamics and change in Southern Ocean ecosystems. J Mar Syst 161:26–41

Convey P, Barnes DKA, Griffiths HJ et al (2011) Biogeography and regional classifications of Antarctica. In: Rogers AD, Johnston NM, Murphy EJ, Clarke A (eds) Antarctic ecosystems: an extreme environment in a changing world. Wiley, Hoboken, pp 469–491

Corsolini S, Covaci A, Ademollo N et al (2006) Occurrence of organochlorine pesticides (OCPs) and their enantiomeric signatures, and concentrations of polybrominated diphenyl ethers (PBDEs) in the Adélie penguin food web, Antarctica. Environ Pollut 140:371–382. https://doi.org/10.1016/j.envpol.2005.04.039

Cotté C, Guinet C (2007) Historical whaling records reveal major regional retreat of Antarctic sea ice. Deep Sea Res Part 1 Oceanogr Res Pap 54:243–252. https://doi.org/10.1016/j.dsr.2006.11.001

Croxall JP, Steele WK, McInnes SJ, Prince P (1995) Breeding distribution of the Snow Petrel *Pagodroma nivea*. Mar Ornithol 23:69–100

de Baar HJWW, Bathmannt U, Smetacek V et al (1995) Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. Nature 373:412–415. https://doi.org/10.1038/373412a0

de Steur L, Holland DM, Muench RD, McPhee MG (2007) The warmwater "Halo" around Maud Rise: properties, dynamics and Impact. Deep Sea Res Part 1 Oceanogr Res Pap 54:871–896. https://doi.org/10.1016/j.dsr.2007.03.009

De Broyer C, Danis B, Louise A et al (2011) How many species in the Southern Ocean? Towards a dynamic inventory of the Antarctic marine species. Deep-Sea Res Part II 58:5–17. https://doi.org/10.1016/j.dsr2.2010.10.007

De Rydt J, Hilmar Gudmundsson G, Nagler T et al (2018) Recent rift formation and impact on the structural integrity of the Brunt Ice Shelf, East Antarctica. Cryosphere 12:505–520. https://doi.org/10.5194/tc-12-505-2018

de la Mare WK (1997) Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. Nature 389:57–60. https://doi.org/10.1038/37956

DeBroyer C (1977) Analysis of the gigantism and dwarfness of Antarctic and Subantarctic Gammaridean Amphipoda. In: Adaptations within Antarctic ecosystems. pp 327–334

Decelle J, Probert I, Bittner L et al (2012) An original mode of symbiosis in open ocean plankton. Proc Natl Acad Sci USA 109:18000–18005. https://doi.org/10.1073/pnas.1212303109

Dell R, Arnold N, Willis I et al (2020) Lateral meltwater transfer across an Antarctic ice shelf. Cryosphere 14:2313–2330. https://doi.org/10.5194/tc-14-2313-2020

Delord K, Kato A, Tarroux A et al (2020) Antarctic petrels 'on the ice rocks': wintering strategy of an Antarctic seabird. R Soc Open Sci 7:191429. https://doi.org/10.1098/rsos.191429

Descamps S, Tarroux A, Cherel Y et al (2016a) At-sea distribution and prey selection of antarctic petrels and commercial krill fisheries. PLoS ONE 11:e0156968. https://doi.org/10.1371/journal.pone.0156968

Descamps S, Tarroux A, Lorentsen SH et al (2016b) Large-scale oceanographic fluctuations drive Antarctic petrel survival and reproduction. Ecography 39:496–505. https://doi.org/10.1111/ecog.01659

Divine DV, Koç N, Isaksson E et al (2010) Holocene Antarctic climate variability from ice and marine sediment cores: insights on ocean-atmosphere interaction. Quat Sci Rev 29:303–312. https://doi.org/10.1016/j.quascirev.2009.11.012

Dong J, Speer K, Jullion L (2016) The Antarctic slope current near 30°E. J Geophys Res 121:1051–1062. https://doi.org/10.1002/2015JC011099

Dorschel B, Gutt J, Piepenburg D et al (2014) The influence of the geomorphological and sedimentological settings on the distribution of epibenthic assemblages on a flat topped hill on the over-deepened shelf of the western Weddell Sea (Southern Ocean). Biogeosciences 11:3797–3817. https://doi.org/10.5194/bg-11-3797-2014

Douglass LL, Turner J, Grantham HS et al (2014) A hierarchical classification of benthic biodiversity and assessment of protected areas in the Southern Ocean. PLoS ONE. https://doi.org/10.1371/journal.pone.0100551

Drews R, Pattyn F, Hewitt IJ et al (2017) Actively evolving subglacial conduits and eskers initiate ice shelf channels at an Antarctic grounding line. Nat Commun 8:15228. https://doi.org/10.1038/ncomms15228

Drews R, Schannwell C, Ehlers TA et al (2020) Atmospheric and oceanographic signatures in the ice shelf channel morphology of Roi Baudouin ice shelf, East Antarctica, inferred from radar data. J Geophys Res Earth Surf. https://doi.org/10.1029/2020JF005587

del Hoyo J, Elliott A, Sargatal J (1996) Handbook of the Birds of the World, Volume 3: Hoatzin to Auks. Lynx Edicions, Barcelona, Spain

Edinburgh T, Day JJ (2016) Estimating the extent of Antarctic summer sea ice during the Heroic Age of Antarctic exploration. Cryosphere 10:2721–2730. https://doi.org/10.5194/tc-10-2721-2016

Efremenko VN (1991) Ichthyoplankton studies in the Lazarev Sea. J Ichthyol 32:129–133

Eicken H, Lange MA, Wadhams P (1994) Characteristics and distribution patterns of snow and meteoric ice in the Weddell Sea and their contribution to the mass balance of sea ice. Ann Geophys 12:80–93. https://doi.org/10.1007/s00585-994-0080-x

Eisermann H, Eagles G, Ruppel A et al (2020) Bathymetry beneath ice shelves of western Dronning Maud Land, East Antarctica, and implications on ice shelf stability. Geophys Res Lett. https://doi.org/10.1029/2019GL086724

Eisermann H, Eagles G, Ruppel AS et al (2021) Bathymetric control on Borchgrevink and Roi Baudouin Ice Shelves in East Antarctica. J Geophys Res Earth Surf. https://doi.org/10.1029/2021JF006342

Ekau W (1986) Demersal fish fauna of the Weddell sea, Antarctica. Antarct Sci 2:129–137. https://doi.org/10.1017/S0954102090000165

El-Sayed SZ (2013) Observations on phytoplankton bloom in the weddell sea. In: Biology of the Antarctic seas IV. pp 301–312

Eriksen M, Lebreton LCM, Carson HS et al (2014) Plastic pollution in the world's oceans: more than 5 Trillion plastic pieces weighing over 250,000 tons Afloat at Sea. PLoS ONE. https://doi.org/10.1371/journal.pone.0111913

Fahrbach E, Rohardt G, Krause G (1992) The Antarctic coastal current in the southeastern Weddell Sea. Polar Biol 12:171–182. https://doi.org/10.1007/BF00238257

Fahrbach E, Peterson RG, Rohardt G et al (1994) Suppression of bottom water formation in the southeastern Weddell Sea. Deep-Sea Res Part I 41:389–411. https://doi.org/10.1016/0967-0637(94)90010-8

Falk-Petersen S, Sargent JR, Lønne OJ, Timofeev S (1999) Functional biodiversity of lipids in Antarctic zooplankton: *Calanoides acutus*, *Calanus propinquus*, *Thysanoessa macrura* and *Euphausia crystallorophias*. Polar Biol 21:37–47. https://doi.org/10.1007/s003000050330

Fauchald P, Tveraa T (2006) Hierarchical patch dynamics and animal movement pattern. Oecologia 149:383–395. https://doi.org/10.1007/s00442-006-0463-7

Fauchald P, Tarroux A, Tveraa T et al (2017) Spring phenology shapes the spatial foraging behavior of Antarctic petrels. Mar Ecol Prog Ser 568:203–215. https://doi.org/10.3354/meps12082

Favier L, Pattyn F, Berger S, Drews R (2016) Dynamic influence of pinning points on marine ice-sheet stability: a numerical study in Dronning Maud Land, East Antarctica. Cryosphere 10:2623–2635. https://doi.org/10.5194/tc-10-2623-2016

Figuerola B, Hancock AM, Bax N et al (2021) A Review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the southern ocean. Front Mar Sci 8:584445

Flores H, Van De Putte AP, Siegel V et al (2008) Distribution, abundance and ecological relevance of pelagic fishes in the Lazarev Sea, Southern Ocean. Mar Ecol Prog Ser 367:271–282. https://doi.org/10.3354/meps07530

Flores H, van Franeker JA, Cisewski B et al (2011) Macrofauna under sea ice and in the open surface layer of the Lazarev Sea, Southern Ocean. Deep-Sea Res Part II 58:1948–1961. https://doi.org/10.1016/j.dsr2.2011.01.010

Flores H, van Franeker JA, Siegel V et al (2012) The association of Antarctic krill *Euphausia superba* with the under-ice habitat. PLoS ONE. https://doi.org/10.1371/journal.pone.0031775

Flores H, Hunt BPV, Kruse S et al (2014) Seasonal changes in the vertical distribution and community structure of Antarctic macrozooplankton and micronekton. Deep Sea Res Part 1 Oceanogr Res Pap 84:127–141. https://doi.org/10.1016/j.dsr.2013.11.001

Forsberg CF, Loøvlie R, Jansen E et al (2003) A 1.3-Myr palaeoceanographic record from the continental margin off Dronning Maud Land, Antarctica. Palaeogeogr Palaeoclimatol Palaeoecol 198:223–235. https://doi.org/10.1016/S0031-0182(03)00402-4

Francis D, Eayrs C, Cuesta J, Holland D (2019) Polar cyclones at the origin of the reoccurrence of the Maud Rise Polynya in Austral winter 2017. J Geophys Res 124:5251–5267. https://doi.org/10.1029/2019JD030618

Fransson A, Chierici M, Anderson L, David R (2004a) Transformation of carbon and oxygen in the surface layer of the eastern Atlantic sector of the Southern Ocean. Deep-Sea Res Part II 51:2757–2772. https://doi.org/10.1016/j.dsr2.2001.12.001

Fransson A, Chierici M, Anderson LG (2004b) Diurnal variability in the oceanic carbon dioxide system and oxygen in the Southern Ocean surface water. Deep-Sea Res Part II 51:2827–2839. https://doi.org/10.1016/j.dsr2.2001.01.001

Fraser A, Massom R, Ohshima K et al (2020) High-resolution mapping of circum-Antarctic landfast sea ice distribution, 2000–2018. Earth Syst Sci Data Discuss. https://doi.org/10.5194/essd-2020-99

Fraser AD, Massom RA, Handcock MS et al (2021) Eighteen-year record of circum-Antarctic landfast-sea-ice distribution allows detailed baseline characterisation and reveals trends and variability. Cryosphere 15:5061–5077. https://doi.org/10.5194/tc-15-5061-2021

Freer JF, Tarling GA, Collins MA, Partridge JC, Genner MJ (2019) Predicting future distributions of lanternfish, a significant ecological resource within the Southern Ocean. Divers Distrb 25:1259–1272. https://doi.org/10.1111/ddi.12934

Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies. Glob Ecol Biogeogr 18:543–552. https://doi.org/10.1111/j.1466-8238.2009.00467.x

Fretwell PT, Trathan PN (2021) Discovery of new colonies by Sentinel2 reveals good and bad news for emperor penguins. Remote Sens Ecol Conserv 7:139–153. https://doi.org/10.1002/rse2.176

Fretwell PT, LaRue MA, Morin P et al (2012) An emperor penguin population estimate: the first global, synoptic survey of a species from space. PLoS ONE 7:e33751. https://doi.org/10.1371/journal.pone.0033751

Fretwell P, Pritchard HD, Vaughan DG et al (2013) Bedmap 2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7:375–393. https://doi.org/10.5194/tc-7-375-2013

Frölicher TL, Sarmiento JL, Paynter DJ et al (2015) Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. J Clim 28:862–886. https://doi.org/10.1175/JCLI-D-14-00117.1

Froneman PW (2004) Protozooplankton community structure and grazing impact in the eastern Atlantic sector of the Southern Ocean in austral summer 1998. Deep-Sea Res Part II 51:2633–2643. https://doi.org/10.1016/j.dsr2.2004.09.001

Froneman PW, Mcquaid CD, Perissinotto R (1995) Biogeographic structure of the microphytoplankton assemblages of the south Atlantic and Southern Ocean during austral summer. J Plankton Res 17:1791–1802. https://doi.org/10.1093/plankt/17.9.1791

Fulton EA (2010) Approaches to end-to-end ecosystem models. J Mar Syst 81:171–183. https://doi.org/10.1016/j.jmarsys.2009.12.012

Fulton EA, Bax NJ, Bustamante RH et al (2015) Modelling marine protected areas: insights and hurdles. Philos Trans R Soc B 370:20140278

Fürst JJ, Durand G, Gillet-Chaulet F et al (2016) The safety band of Antarctic ice shelves. Nat Clim Change 6:479–482. https://doi.org/10.1038/nclimate2912

Galéron J, Herman RL, Arnaud PM et al (1992) Macrofaunal communities on the continental shelf and slope of the southeastern Weddell Sea, Antarctica. Polar Biol 12:283–290. https://doi.org/10.1007/BF00238271

Gallaher D, Campbell GG, Meier W et al (2015) The process of bringing dark data to light: the rescue of the early Nimbus satellite data. GeoResJ 6:124–134. https://doi.org/10.1016/j.grj.2015.02.013

Gardner AS, Moholdt G, Scambos T et al (2017) Increased West Antarctic ice discharge and East Antarctic stability over the last seven years. Cryosphere Discuss 2017:1–39. https://doi.org/10.5194/tc-2017-75

Garrison DL, Jeffries MO, Gibson A et al (2003) Development of sea ice microbial communities during autumn ice formation in the Ross Sea. Mar Ecol Prog Ser 259:1–15. https://doi.org/10.3354/meps259001

Gerdes D, Klages M, Arntz WE et al (1992) Quantitative investigations on macrobenthos communities of the southeastern Weddell Sea shelf based on multibox corer samples. Polar Biol 12:291–301. https://doi.org/10.1007/BF00238272

Gerdes D, Hilbig B, Montiel A (2003) Impact of iceberg scouring on macrobenthic communities in the high-Antarctic Weddell Sea. Polar Biol 26:295–301. https://doi.org/10.1007/s00300-003-0484-1

Gibson JAE, Andersen DT (2002) Physical structure of epishelf lakes of the southern Bunger Hills, East Antarctica. Antarct Sci 14:253–261. https://doi.org/10.1017/S095410200200010X

Goel V, Martín C, Matsuoka K (2018) Ice-rise stratigraphy reveals changes in surface mass balance over the last millennia in Dronning Maud Land. J Glaciol 64:932–942. https://doi.org/10.1017/jog.2018.81

Goel V, Matsuoka K, Berger CD et al (2020) Characteristics of ice rises and ice rumples in Dronning Maud Land and Enderby Land, Antarctica. J Glaciol 66:1064–1078. https://doi.org/10.1017/jog.2020.77

Gordon AL (1978) Deep Antarctic Convection West of Maud Rise. J Phys Oceanogr 8:600–612. https://doi.org/10.1175/1520-0485(1978)008%3c0600:dacwom%3e2.0.co;2

Graham JA, Heywood KJ, Chavanne CP, Holland PR (2013) Seasonal variability of water masses and transport on the Antarctic continental shelf and slope in the southeastern Weddell Sea. J Geophys Res 118:2201–2214. https://doi.org/10.1002/jgrc.20174

Graham RM, De Boer AM, van Sebille E et al (2015) Inferring source regions and supply mechanisms of iron in the Southern Ocean from satellite chlorophyll data. Deep Sea Res Part 1 Oceanogr Res Pap 104:9–25. https://doi.org/10.1016/j.dsr.2015.05.007

Griffiths HJ, Meijers AJ, Bracegirdle TJ (2017) More losers than winners in a century of future Southern Ocean seafloor warming. Nat Clim Chang 7:749–754

Griffiths HJ, Whittle RJ, Roberts S et al (2014) Decapoda: crabs and lobster. In: Biogeographic Atlas of the Southern Ocean. pp 185–189

Gudmundsson GH, De Rydt J, Nagler T (2017) Five decades of strong temporal variability in the flow of Brunt Ice Shelf, Antarctica. J Glaciol 63:164–175. https://doi.org/10.1017/jog.2016.132

Guerrero-Kommritz J (2011) Seasonal distribution of early life stages in squid of the Lazarev Sea, Antarctica. Antarct Sci 23:93–94. https://doi.org/10.1017/S0954102010000672

Gurarie E, Bengtson JL, Bester MN et al (2017) Distribution, density and abundance of Antarctic ice seals off Queen Maud Land and the eastern Weddell Sea. Polar Biol 40:1149–1165. https://doi.org/10.1007/s00300-016-2029-4

Gutt J (2007) Antarctic macro-zoobenthic communities: a review and an ecological classification. Antarct Sci 19:165–182

Gutt J, Ekau W (1996) Habitat partitioning of dominant high Antarctic demersal fish in the Weddell Sea and Lazarev Sea. J Exp Mar Biol Ecol 206:25–37. https://doi.org/10.1016/0022-0981(95)00186-7

Gutt J, Piepenburg D (2003) Scale-dependent impact on diversity of Antarctic benthos caused by grounding of icebergs. Mar Ecol Prog Ser 253:77–83. https://doi.org/10.3354/meps253077

Gutt J, Starmans A (1998) Structure and biodiversity of megabenthos in the Weddell and Lazarev Seas (Antarctica): ecological role of physical parameters and biological interactions. Polar Biol 20:229–247. https://doi.org/10.1007/s003000050300

Gutt J, Ekau W, Gorny M (1994) New Results on the Fish and Shrimp fauna of the Weddell Sea and Lazarev Sea (Antartic). Proc NIPR Symp Plolar Biol 7:91–102

Gutt J, Barnes DKA, Lockhart SJ, Van De Putte A (2013a) Antarctic macrobenthic communities: a compilation of circumpolar information. Nat Conserv 4:1–13

Gutt J, Griffiths HJ, Jones CD (2013b) Circumpolar overview and spatial heterogeneity of Antarctic macrobenthic communities. Mar Biodivers 43:481–487. https://doi.org/10.1007/s12526-013-0152-9

Hallanger IG, Ruus A, Herzke D et al (2011) Influence of season, location, and feeding strategy on bioaccumulation of halogenated organic contaminants in Arctic marine zooplankton. Environ Toxicol Chem 30:77–87. https://doi.org/10.1002/etc.362

Hall-Martin AJ (1974) Observations on population density and species composition of seals in the King-Haakon-VII Sea Antarctica. S Afr J Antarct Res 4:34–39

Han Y, Huh Y, Hong S et al (2011) Quantification of total mercury in antarctic surface snow using ICP-SF-MS: spatial variation from the coast to dome fuji. Bull Korean Chem Soc 32:4258–4264. https://doi.org/10.5012/bkcs.2011.32.12.4258

Handley J, Rouyer MM, Pearmain EJ et al (2021) Marine important bird and biodiversity areas for Penguins in Antarctica, targets for conservation action. Front Mar Sci. https://doi.org/10.3389/fmars.2020.602972

Hansen HE (1934) Limits of the pack-ice in the Antarctic in the area between 40° W and 110° E. Hvalradets Skr 9:39–41

Hansen HE (1936) Atlas over Antarktis og Sydishavet. Geogr Ann 19(2):134–135

Haraldsson M, Siegel V (2014) Seasonal distribution and life history of *Thysanoessa macrura* (Euphausiacea, Crustacea) in high latitude waters of the Lazarev Sea, Antarctica. Mar Ecol Prog Ser 495:105–118. https://doi.org/10.3354/meps10553

Hass HC, Kuhn G, Klages JP, Forwick M (2016) A Large channel system in the Western Riiser Larsen Sea, East Antarctica: Paleoceanographic and sedimentary aspects. In: EPIC3EGU General Assembly 2016, Vienna, Austria, 2016-04-2016-04

Hattermann T (2018) Antarctic thermocline dynamics along a narrow shelf with easterly winds. J Phys Oceanogr 48:2419–2443. https://doi.org/10.1175/JPO-D-18-0064.1

Hattermann T, Nst OA, Lilly JM, Smedsrud LH (2012) Two years of oceanic observations below the Fimbul Ice shelf Antarctica. Geophys Res Lett. https://doi.org/10.1029/2012GL051012

Hattermann T, Smedsrud LH, Nøst OA et al (2014) Eddy-resolving simulations of the Fimbul Ice Shelf cavity circulation: Basal melting and exchange with open ocean. Ocean Model 82:28–44. https://doi.org/10.1016/j.ocemod.2014.07.004

Hauck J, Gerdes D, Hillenbrand CD et al (2012) Distribution and mineralogy of carbonate sediments on Antarctic shelves. J Mar Syst 90:77–87. https://doi.org/10.1016/j.jmarsys.2011.09.005

Hayakawa H, Shibuya K, Aoyama Y et al (2012) Ocean bottom pressure variability in the Antarctic divergence zone off Lützow-Holm Bay, East Antarctica. Deep Sea Res Part 1 Oceanogr Res Pap 60:22–31. https://doi.org/10.1016/j.dsr.2011.09.005

Hegseth EN, von Quillfeldt CH (2002) Low phytoplankton biomass and ice algal blooms in the Weddell Sea during the ice-filled summer of 1997. Antarct Sci 14:231–243. https://doi.org/10.1017/s095410200200007x

Heil P, Gerland S, Granskog MA (2011) An Antarctic monitoring initiative for fast ice and comparison with the Arctic. Cryosphere Discuss 5:2437–2463. https://doi.org/10.5194/tcd-5-2437-2011

Hellmer HH, Kauker F, Timmermann R et al (2012) Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. Nature 485:225–228. https://doi.org/10.1038/nature11064

Hellmer HH, Kauker F, Timmermann R, Hattermann T (2017) The fate of the Southern Weddell Sea continental shelf in a warming climate. J Clim 30:4337–4350. https://doi.org/10.1175/JCLI-D-16-0420.1

Helm V, Humbert A, Miller H (2014) Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. Cryosphere 8(4):1539–1559

Henjes J, Assmy P, Klaas C, Smetacek V (2007) Response of the larger protozooplankton to an iron-induced phytoplankton bloom in the Polar Frontal Zone of the Southern Ocean (EisenEx). Deep Sea Res Part 1 Oceanogr Res Pap 54:774–791. https://doi.org/10.1016/j.dsr.2007.02.005

Heywood KJ, Locarnini RA, Frew RD, et al (2013) Transport and water masses of the Antarctic slope front system in the Eastern Weddell Sea. pp 203–214

Hindell MA, Reisinger RR, Ropert-Coudert Y et al (2020) Tracking of marine predators to protect Southern Ocean ecosystems. Nature 580:87–92. https://doi.org/10.1038/s41586-020-2126-y

Hinz K, Neben S, Gouseva YB, Kudryavtsev GA (2004) A Compilation of Geophysical Data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica. Mar Geophys Res 25:233–245. https://doi.org/10.1007/s11001-005-1319-y

Hjort C, Björck S, Ingólfsson Ó, Möller P (1998) Holocene deglaciation and climate history of the northern Antarctic Peninsula region: a discussion of correlations between the Southern and

Northern Hemispheres. Ann Glaciol 27:110–112. https://doi.org/10.3189/1998aog27-1-110-112

Hobson KA, Wassenaar LI (1999) Stable isotope ecology: an introduction. Oecologia 120:312–313. https://doi.org/10.1007/s004420050864

Hoddell RJ, Crossley AC, Williams R, Hosie GW (2000) The distribution of Antarctic pelagic fish and larvae (CCAMLR division 58.4.1). Deep-Sea Res Part II 47:2519–2541. https://doi.org/10.1016/S0967-0645(00)00034-5

Hodell DA, Brenner M, Curtis JH, Guilderson T (2001) Solar forcing of drought frequency in the Maya lowlands. Science 292:1367–1370. https://doi.org/10.1126/science.1057759

Hodum PJ, Hobson KA (2000) Trophic relationships among Antarctic fulmarine petrels: Insights into dietary overlap and chick provisioning strategies inferred from stable-isotope ($\delta^{15}N$ and $\delta^{13}C$) analyses. Mar Ecol Prog Ser 198:273–281. https://doi.org/10.3354/meps198273

Holland DM (2001) Explaining the Weddell Polynya: a large ocean eddy shed at Maud Rise. Science 292:1697–1700. https://doi.org/10.1126/science.1059322

Holland PR (2014) The seasonality of Antarctic sea ice trends. Geophys Res Lett 41:4230–4237. https://doi.org/10.1002/2014GL060172

Holland PR, Kwok R (2012) Wind-driven trends in Antarctic sea-ice drift. Nat Geosci 5:872–875. https://doi.org/10.1038/ngeo1627

Hoppema M (2004a) Weddell Sea is a globally significant contributor to deep-sea sequestration of natural carbon dioxide. Deep Sea Res Part 1 Oceanogr Res Pap 51:1169–1177. https://doi.org/10.1016/j.dsr.2004.02.011

Hoppema M (2004b) Weddell Sea turned from source to sink for atmospheric CO_2 between pre-industrial time and present. Glob Planet Change 40:219–231. https://doi.org/10.1016/j.gloplacha.2003.08.001

Hoppema M, Fahrbach E, Schröder M et al (1995) Winter-summer differences of carbon dioxide and oxygen in the Weddell Sea surface layer. Mar Chem 51:177–192. https://doi.org/10.1016/0304-4203(95)00065-8

Hoppema M, Fahrbach E, Stoll MH, De Baar HJW (1999) Annual uptake of atmospheric CO_2 by the Weddell sea derived from a surface layer balance, including estimations of entrainment and new production. J Mar Syst 19:219–233. https://doi.org/10.1016/S0924-7963(98)00091-8

Hoppema M, Stoll MHC, De Baar HJW (2000) CO_2 in the Weddell Gyre and Antarctic circumpolar current: Austral autumn and early winter. Mar Chem 72:203–220. https://doi.org/10.1016/S0304-4203(00)00082-7

Hoppema M, Roether W, Bellerby RGJ, De Baar HJW (2001) Direct measurements reveal insignificant storage of anthropogenic CO_2 in the abyssal Weddell Sea. Geophys Res Lett 28:1747–1750. https://doi.org/10.1029/2000GL012443

Hoppema M, Middag R, De Baar HJW et al (2007) Whole season net community production in the Weddell Sea. Polar Biol 31:101–111. https://doi.org/10.1007/s00300-007-0336-5

Hopkins TL, Ainley DG, Torres JJ, Lancraft TM (1993) Trophic structure in open waters of the marginal ice zone in the Scotia-Weddell confluence region during spring (1983). Polar Biol 13:389–397. https://doi.org/10.1007/BF01681980

Hoppmann M, Nicolaus M, Paul S et al (2015) Ice platelets below Weddell Sea landfast sea ice. Ann Glaciol 56:175–190. https://doi.org/10.3189/2015AoG69A678

Horner RA, Syvertsen EE, Thomas DP, Lange C (1988) Proposed terminology and reporting units for sea ice algal assemblages. Polar Biol 8:249–253. https://doi.org/10.1007/BF00263173

Hosie GW, Fukuchi M, Kawaguchi S (2003) Development of the Southern Ocean Continuous Plankton Recorder survey. Prog Oceanogr 58:263–283

Huang ZJ, Savage SB (1998) Particle-in-cell and finite difference approaches for the study of marginal ice zone problems. Cold Reg Sci Technol 28(1):1–28

Hubbard B, Luckman A, Ashmore DW et al (2016) Massive subsurface ice formed by refreezing of ice-shelf melt ponds. Nat Commun. https://doi.org/10.1038/ncomms11897

Humbert A, Steinhage D (2011) The evolution of the western rift area of the Fimbul Ice Shelf, Antarctica. Cryosphere 5:931–944. https://doi.org/10.5194/tc-5-931-2011

Humbert A, Steinhage D, Helm V et al (2015) On the link between surface and basal structures of the Jelbart Ice Shelf, Antarctica. J Glaciol 61:975–986. https://doi.org/10.3189/2015JoG15J023

Hunkeler PA, Hendricks S, Hoppmann M et al (2015) Towards an estimation of sub-sea-ice platelet-layer volume with multi-frequency electromagnetic induction sounding. Ann Glaciol 56:137–146. https://doi.org/10.3189/2015AoG69A705

Hunt BPV, Pakhomov EA, Siegel V et al (2011) The seasonal cycle of the Lazarev Sea macrozooplankton community and a potential shift to top-down trophic control in winter. Deep-Sea Res Part II 58:1662–1676. https://doi.org/10.1016/j.dsr2.2010.11.016

Hunt GL, Drinkwater KF, Arrigo K et al (2016) Advection in polar and sub-polar environments: impacts on high latitude marine ecosystems. Prog Oceanogr 149:40–81

Jansen D, Luckman A, Kulessa B et al (2013) Marine ice formation in a suture zone on the Larsen C Ice Shelf and its influence on ice shelf dynamics. J Geophys Res Earth Surf 118:1628–1640. https://doi.org/10.1002/jgrf.20120

Jenkins A, Shoosmith D, Dutrieux P et al (2018) West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. Nat Geosci 11:733–738. https://doi.org/10.1038/s41561-018-0207-4

Jenouvrier S, Holland M, Stroeve J et al (2014) Projected continent-wide declines of the emperor penguin under climate change. Nat Clim Change 4:715–718. https://doi.org/10.1038/nclimate2280

Jerosch K, Kuhn G, Krajnik I et al (2016) A geomorphological seabed classification for the Weddell Sea, Antarctica. Mar Geophys Res 37:127–141. https://doi.org/10.1007/s11001-015-9256-x

Johansson P, Thor G (2004) Observations on the birds of the Vestfjella and Heimefrontfjella, Dronning Maud Land, Antarctica, 1991/92 and 2001/02. Mar Ornithol 32:43–46

Joiris CR, Humphries GRW, De Broyer A (2013) Seabirds encountered along return transects between South Africa and Antarctica in summer in relation to hydrological features. Polar Biol 36:1633–1647. https://doi.org/10.1007/s00300-013-1382-9

Jokat W, Boebel T, König M, Meyer U (2003) Timing and geometry of early Gondwana breakup. J Geophys Res. https://doi.org/10.1029/2002jb001802

Jourdain N, Asay-Davis X, Hattermann T et al (2019) A protocol for calculating basal melt rates in the ISMIP6 Antarctic ice sheet projections. Cryosphere Discuss. https://doi.org/10.5194/tc-2019-277

Kaiser S, Brandão SN, Brix S et al (2013) Patterns, processes and vulnerability of Southern Ocean benthos: a decadal leap in knowledge and understanding. Mar Biol 160:2295–2317

Kallenborn R, Breivik K, Eckhardt S et al (2013) Long-term monitoring of persistent organic pollutants (POPs) at the Norwegian Troll station in Dronning Maud Land, Antarctica. Atmos Chem Phys 13:6983–6992. https://doi.org/10.5194/acp-13-6983-2013

Kane JE (1966) The distribution of *Parathemisto gaudichaudii* (Guer.), with observations on its life-history in the 0° to 20° E sector in the Southern Ocean. Cambridge University Press, London, pp 163–198

Kasamatsu F (1995) Current status of Odontocetes in the Antarctic. Antarct Sci 7:365–379. https://doi.org/10.1017/S0954102095000514

Kasamatsu F, Ensor P, Joyce GG (1998) Clustering and aggregations of minke whales in the Antarctic feeding grounds. Mar Ecol Prog Ser 168:1–11. https://doi.org/10.3354/meps168001

Kato A, Ropert-Coudert Y (2006) Rapid increase in Adélie penguin populations in the Lützow-Holm Bay area since the mid 1990s. Polar Biosci 20:55–62

Kauko HM, Hattermann T, Ryan-Keogh T et al (2021) Phenology and environmental control of phytoplankton blooms in the Kong Håkon VII Hav in the Southern Ocean. Front Mar Sci. https://doi.org/10.3389/fmars.2021.623856

Kausch T, Lhermitte S, Lenaerts J et al (2020) Impact of coastal East Antarctic ice rises on surface mass balance: insights from observations and modeling. Cryosphere Discuss. https://doi.org/10.5194/tc-2020-66

Kawaguchi S, Ishida A, King R et al (2013) Risk maps for Antarctic krill under projected Southern Ocean acidification. Nat Clim Change 3:843–847. https://doi.org/10.1038/nclimate1937

Kawamura T (1997) Physical, structural, and isotopic characteristics and growth processes of fast sea ice in Lützow-Holm Bay, Antarctica. J Geophys Res C 102:3345–3355. https://doi.org/10.1029/96JC03206

Khatiwala S, Primeau F, Hall T (2009) Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. Nature 462:346–349. https://doi.org/10.1038/nature08526

Kingslake J, Ely JC, Das I, Bell RE (2017) Widespread movement of meltwater onto and across Antarctic ice shelves. Nature 544:349–352. https://doi.org/10.1038/nature22049

Klaas C (1997) Microprotozooplankton distribution and their potential grazing impact in the Antarctic circumpolar current. Deep-Sea Res Part II 44:375–393. https://doi.org/10.1016/S0967-0645(96)00080-X

Klaas C (2001) Spring distribution of larger (>64-µm) protozoans in the Atlantic sector of the Southern Ocean. Deep Sea Res Part 1 Oceanogr Res Pap 48:1627–1649. https://doi.org/10.1016/S0967-0637(00)00088-1

Klages N (1989) Food and feeding ecology of emperor penguins in the eastern Weddell Sea. Polar Biol 9:385–390. https://doi.org/10.1007/BF00442529

Kock KH (1992) Antarctic fish and fisheries. Antarct Fish Fish. https://doi.org/10.2307/5212

Kock KH (2007) Antarctic marine living resources: exploitation and its management in the Southern Ocean. Antarct Sci 19:231–238. https://doi.org/10.1017/S0954102007000302

Krafft BA, Melle W, Knutsen T et al (2010) Distribution and demography of Antarctic krill in the Southeast Atlantic sector of the Southern Ocean during the austral summer 2008. Polar Biol 33:957–968. https://doi.org/10.1007/s00300-010-0774-3

Krapp RH, Berge J, Flores H et al (2008) Sympagic occurrence of Eusirid and Lysianassoid amphipods under Antarctic pack ice. Deep-Sea Res Part II 55:1015–1023. https://doi.org/10.1016/j.dsr2.2007.12.018

Kristiansen S, Farbrot T, Kuosa H et al (1998) Nitrogen uptake in the infiltration community, an ice algal community in Antarctic pack-ice. Polar Biol 19:307–315. https://doi.org/10.1007/s003000050251

Kuhn G, Weber ME (1993) Acoustical characterization of sediments by Parasound and 3.5 kHz systems: related sedimentary processes on the southeastern Weddell Sea continental slope. Antarct Mar Geol 113:201–217. https://doi.org/10.1016/0025-3227(93)90018-Q

Kuklinski P, Wicikowski L, Koper M et al (2019) Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. Mar Pollut Bull. https://doi.org/10.1016/j.marpolbul.2019.110573

Kunzmann A, Zimmermann C (1992) Aethotaxis mitopteryx, a high-Antarctic fish with benthopelagic mode of life. Mar Ecol Prog Ser 88:33–40. https://doi.org/10.3354/meps088033

Kvile KO, Taranto GH, Pitcher TJ, Morato T (2014) A global assessment of seamount ecosystems knowledge using an ecosystem evaluation framework. Biol Conserv 173:108–120. https://doi.org/10.1016/j.biocon.2013.10.002

Kwok R, Kacimi S (2018) Three years of sea ice freeboard, snow depth, and ice thickness of the weddell sea from operation icebridge and cryosat-2. Cryosphere 12:2789–2801. https://doi.org/10.5194/tc-12-2789-2018

Labrousse S, Vacquié-Garcia J, Heerah K et al (2015) Winter use of sea ice and ocean water mass habitat by southern elephant seals: the length and breadth of the mystery. Prog Oceanogr 137:52–68. https://doi.org/10.1016/j.pocean.2015.05.023

Landschützer P, Gruber N, Haumann FA et al (2015) The reinvigoration of the Southern Ocean carbon sink. Science 349:1221–1224. https://doi.org/10.1126/SCIENCE.AAB2620

Lange MA, Schlosser P, Ackley SF et al (1990) 18O concentrations in sea ice of the Weddell Sea, Antarctica. J Glaciol 36:315–323. https://doi.org/10.3189/002214390793701291

Langley K, Kohler J, Sinisalo A et al (2014a) Low melt rates with seasonal variability at the base of Fimbul Ice Shelf, East Antarctica, revealed by in situ interferometric radar measurements. Geophys Res Lett 41:8138–8146. https://doi.org/10.1002/2014GL061782

Langley K, Von Deschwanden A, Kohler J et al (2014b) Complex network of channels beneath an Antarctic ice shelf. Geophys Res Lett 41:1209–1215. https://doi.org/10.1002/2013GL058947

Le Quéré C, Rödenbeck C, Buitenhuis ET et al (2007) Saturation of the southern ocean CO_2 sink due to recent climate change. Science 316:1735–1738. https://doi.org/10.1126/science.1136188

Leadley PW, Krug CB, Alkemade R, et al (2017) Progress towards the Aichi Biodiversity Targets: an assessment of biodiversity trends, policy scenarios and key actions

Legendre L, Ackley SF, Dieckmann GS et al (1992) Ecology of sea ice biota - 2. Glob Signif Polar Biol 12:429–444. https://doi.org/10.1007/BF00243114

Lenaerts JTM, Van Meijgaard E, Van Den Broeke MR et al (2013) Recent snowfall anomalies in Dronning Maud Land, East Antarctica, in a historical and future climate perspective. Geophys Res Lett 40:2684–2688. https://doi.org/10.1002/grl.50559

Lenaerts JTM, Brown J, Van Broeke MRD et al (2014) High variability of climate and surface mass balance induced by Antarctic ice rises. J Glaciol 60:1126–1134. https://doi.org/10.3189/2014JoG14J040

Lenaerts JTM, Lhermitte S, Drews R et al (2017) Meltwater produced by wind-albedo interaction stored in an East Antarctic ice shelf. Nat Clim Change 7:58–62. https://doi.org/10.1038/nclimate3180

Lenton A, Tilbrook B, Law RM et al (2013) Sea-air CO_2 fluxes in the Southern Ocean for the period 1990–2009. Biogeosciences 10:4037–4054. https://doi.org/10.5194/bg-10-4037-2013

Liebsch N, Wilson RP, Bornemann H et al (2007) Mouthing off about fish capture: jaw movement in pinnipeds reveals the real secrets of ingestion. Deep-Sea Res Part II 54:256–269. https://doi.org/10.1016/j.dsr2.2006.11.014

Lim SM, Moreau S, Vancoppenolle M et al (2019) Field observations and physical-biogeochemical modeling suggest low silicon affinity for Antarctic fast ice diatoms. J Geophys Res 124:7837–7853. https://doi.org/10.1029/2018JC014458

Lindbäck K, Moholdt G, Nicholls KW et al (2019) Spatial and temporal variations in basal melting at Nivlisen ice shelf, East Antarctica, derived from phase-sensitive radars. Cryosphere 13:2579–2595. https://doi.org/10.5194/tc-13-2579-2019

Linse K, Brandt A, Bohn JM et al (2007) Macro- and megabenthic assemblages in the bathyal and abyssal Weddell Sea (Southern Ocean). Deep-Sea Res Part II 54:1848–1863. https://doi.org/10.1016/j.dsr2.2007.07.011

Linse K, Griffiths HJ, Barnes DK et al (2013) The macro- and megabenthic fauna on the continental shelf of the eastern Amundsen Sea, Antarctica. Cont Shelf Res 68:80–90. https://doi.org/10.1016/j.csr.2013.08.012

Lisiecki LE, Raymo ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic δ 18O records. Paleoceanography 20:1–17. https://doi.org/10.1029/2004PA001071

Liu Y, Moore JC, Cheng X et al (2015) Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves. Proc Natl Acad Sci USA 112:3263–3268. https://doi.org/10.1073/pnas.1415137112

Lorentsen SH, Klages N, Røv N (1998) Diet and prey consumption of Antarctic petrels *Thalassoica antarctica* at Svarthamaren, Dronning Maud Land, and at sea outside the colony. Polar Biol 19:414–420

Lubimova TG, Makarov RR, Bibik VA, et al (1988) Interdisciplinary investigations of the pelagic ecosystem in the Commonwealth and Cosmonaut Seas. Collected papers

Lynch HJ, LaRue MA (2014) First global census of the Adélie Penguin. Auk 131:457–466. https://doi.org/10.1642/auk-14-31.1

MacGilchrist GA, Naveira Garabato AC, Brown PJ et al (2019) Reframing the carbon cycle of the subpolar Southern Ocean. Sci Adv. https://doi.org/10.1126/sciadv.aav6410

Maksym T, Stammerjohn SE, Ackley S, Massom R (2012) Antarctic sea ice- A polar opposite? Oceanography 25:140–151. https://doi.org/10.5670/oceanog.2012.88

Marschoff ER, Barrera-Oro ER, Alescio NS, Ainley DG (2012) Slow recovery of previously depleted demersal fish at the South Shetland Islands, 1983–2010. Fish Res 125–126:206–213. https://doi.org/10.1016/j.fishres.2012.02.017

Marshall J, Speer K (2012) Closure of the meridional overturning circulation through Southern Ocean upwelling. Nat Geosci 5:171–180. https://doi.org/10.1038/ngeo1391

Mattsdotter Björk M, Fransson A, Torstensson A, Chierici M (2014) Ocean acidification state in western Antarctic surface waters: controls and interannual variability. Biogeosciences 11:57–73. https://doi.org/10.5194/bg-11-57-2014

Matsuoka K, Hindmarsh RCA, Moholdt G et al (2015) Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution. Earth-Science Rev 150:724–745. https://doi.org/10.1016/j.earscirev.2015.09.004

McBride MM, Dalpadado P, Drinkwater KF et al (2014) Krill, climate, and contrasting future scenarios for Arctic and Antarctic fisheries. ICES J Mar Sci 71:1934–1955

Mcintyre T, Bornemann H, Plötz J et al (2012) Deep divers in even deeper seas: habitat use of male southern elephant seals from Marion Island. Antarct Sci 24:561–570. https://doi.org/10.1017/S0954102012000570

McIntyre T, Stansfield LJ, Bornemann H et al (2013) Hydrographic influences on the summer dive behaviour of Weddell seals (*Leptonychotes weddellii*) in Atka Bay, Antarctica. Polar Biol 36:1693–1700. https://doi.org/10.1007/s00300-013-1384-7

McLeod DJ, Hosie GW, Kitchener JA et al (2010) Zooplankton Atlas of the Southern Ocean: the SCAR SO-CPR Survey (1991–2008). Polar Sci 4:353–385. https://doi.org/10.1016/j.polar.2010.03.004

Mehlum F, Gjessing Y, Haftorn S, Bech C (1988) Census of breeding Antarctic Petrels *Thalassoica antarctica* and physical features of the breeding colony at Svarthamaren, Dronning Maud Land, with notes on breeding Snow Petrels *Pagodroma nivea* and South Polar Skuas *Catharacta maccormicki*. Polar Res 6:1–9. https://doi.org/10.1111/j.1751-8369.1988.tb00576.x

Meiners KM, Vancoppenolle M, Thanassekos S et al (2012) Chlorophyll a in Antarctic sea ice from historical ice core data. Geophys Res Lett. https://doi.org/10.1029/2012GL053478

Menze S, Zitterbart DP, van Opzeeland I, Boebel O (2017) The influence of sea ice, wind speed and marine mammals on southern ocean ambient sound. R Soc Open Sci. https://doi.org/10.1098/rsos.160370

Meredith MP (2013) Replenishing the abyss. Nat Geosci 6:166–167. https://doi.org/10.1038/ngeo1743

Metzl N, Poisson A, Louanchi BC et al (1995) Spatio-temporal distributions of air-sea fluxes of CO_2 in the Indian and Antarctic oceans: a first step. Tellus B 47:56–69. https://doi.org/10.1034/j.1600-0889.47.issue1.7.x

Metzl N, Tilbrook B, Poisson A (1999) The annual fCO_2 cycle and the air-sea CO_2 flux in the sub-Antarctic Ocean. Tellus B 51:849–861. https://doi.org/10.3402/tellusb.v51i4.16495

Metzl N, Brunet C, Jabaud-Jan A et al (2006) Summer and winter air-sea CO_2 fluxes in the Southern Ocean. Deep Sea Res Part 1 Oceanogr Res Pap 53:1548–1563. https://doi.org/10.1016/j.dsr.2006.07.006

Meyer B, Atkinson A, Stöbing D et al (2002) Feeding and energy budgets of Antarctic krill *Euphausia superba* at the onset of winter - I *Furcilia* III Larvae. Limnol Oceanogr 47:943–952. https://doi.org/10.4319/lo.2002.47.4.0943

Meyer B, Auerswald L, Siegel V et al (2009) Seasonal variation in body composition, metabolic activity, feeding, and growth of adult krill *Euphausia superba* in the Lazarev Sea. Mar Ecol Prog Ser 398:1–18. https://doi.org/10.3354/meps08371

Meyer B, Freier U, Grimm V et al (2017) The winter pack-ice zone provides a sheltered but food-poor habitat for larval Antarctic krill. Nat Ecol Evol 1:1853–1861. https://doi.org/10.1038/s41559-017-0368-3

Michels KH, Kuhn G, Hillenbrand C-D et al (2002) The southern Weddell Sea: combined contourite-turbidite sedimentation at the southeastern margin of the Weddell Gyre. Geol Soc Lond 22:305–323. https://doi.org/10.1144/GSL.MEM.2002.022.01.22

Mintenbeck K, Barrera-Oro ER, Brey T et al (2012) Impact of climate change on fishes in complex Antarctic ecosystems. Adv Ecol Res 46:351–426. https://doi.org/10.1016/B978-0-12-396992-7.00006-X

Mizukoshi I, Sunouchi H, Saki T et al (1986) Preliminary report of geological and geophysical surveys off Amery Ice Shelf, East Antarctica. Memoirs 43:48–61

Monteiro PMS, Gregor L, Lévy M et al (2015) Intraseasonal variability linked to sampling alias in air-sea CO_2 fluxes in the Southern Ocean. Geophys Res Lett 42:8507–8514. https://doi.org/10.1002/2015GL066009

Moran AL, Woods HA (2012) Why might they be giants? Towards an understanding of polar gigantism. J Exp Biol 215:1995–2002

Moreau S, di Fiori E, Schloss IR et al (2013) The role of phytoplankton composition and microbial community metabolism in sea-air δpCO2 variation in the Weddell Sea. Deep Sea Res Part 1 Oceanogr Res Pap 82:44–59. https://doi.org/10.1016/j.dsr.2013.07.010

Moreau S, Lannuzel D, Janssens J et al (2019) Sea ice meltwater and circumpolar deep water drive contrasting productivity in three Antarctic polynyas. J Geophys Res 124:2943–2968. https://doi.org/10.1029/2019JC015071

Moreau S, Boyd PW, Strutton PG (2020) Remote assessment of the fate of phytoplankton in the Southern Ocean sea-ice zone. Nat Commun. https://doi.org/10.1038/s41467-020-16931-0

Morley SA, Abele D, Barnes DKA et al (2020) Global drivers on southern ocean ecosystems: changing physical environments and anthropogenic pressures in an earth system. Front Mar Sci. https://doi.org/10.3389/fmars.2020.547188

Morlighem M, Rignot E, Binder T et al (2020) Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the

Antarctic ice sheet. Nat Geosci 13:132–137. https://doi.org/10.1038/s41561-019-0510-8

Mouginot J, Rignot E, Scheuchl B (2014) Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. Geophys Res Lett 41:1576–1584. https://doi.org/10.1002/2013GL059069

Nakajima Y, Watanabe K, Naito Y (1982) Diving observations of the marine benthos at Showa Station, Antarctica. Memoirs 23:44–54

Nakamura K, Doi K, Shibuya K (2010) Fluctuations in the flow velocity of the Antarctic Shirase Glacier over an 11-year period. Polar Sci 4:443–455. https://doi.org/10.1016/j.polar.2010.04.010

Nicholls KW, Østerhus S, Makinson K et al (2009) Ice-ocean processes over the continental shelf of the Southern Weddell Sea, Antarctica: a review. Rev Geophys. https://doi.org/10.1029/2007RG000250

Nielsen SHH, Koç N, Crosta X (2004) Holocene climate in the Atlantic sector of the Southern Ocean: controlled by insolation or oceanic circulation? Geology 32:317–320. https://doi.org/10.1130/G20334.1

Nordøy ES, Blix AS (2009) Movements and dive behaviour of two leopard seals (*Hydrurga leptonyx*) off Queen Maud Land, Antarctica. Polar Biol 32:263–270. https://doi.org/10.1007/s00300-008-0527-8

Nordøy ES, Folkow L, Blix AS et al (1995) Distribution and diving behaviour of crabeater seals (*Lobodon carcinophagus*) off Queen Maud Land. Polar Biol 15:261–268. https://doi.org/10.1007/BF00239846

Norheim G, Somme L, Holt G et al (1982) Mercury and persistent chlorinated hydrocarbons in Antarctic birds from Bouvetoya and Dronning Maud Land. Environ Pollut Ser A 28:233–240. https://doi.org/10.1016/0143-1471(82)90079-4

Nøst OA (2004) Measurements of ice thickness and seabed topography under the Fimbul Ice Shelf, Dronning Maud Land, Antarctica. J Geophys Res C. https://doi.org/10.1029/2004JC002277

Nøst OA, Biuw M, Tverberg V et al (2011) Eddy overturning of the Antarctic slope front controls glacial melting in the Eastern Weddell Sea. J Geophys Res 116:17

Nygård T, Lie E, Rov N, Steinnes E (2001) Metal dynamics in an Antarctic food chain. Mar Pollut Bull 42:598–602. https://doi.org/10.1016/S0025-326X(00)00206-X

Ogundare MO, Fransson A, Chierici M et al (2021) Variability of sea-air carbon dioxide flux in autumn across the Weddell Gyre and offshore dronning Maud Land in the Southern Ocean. Front Mar Sci. https://doi.org/10.3389/fmars.2020.614263

Ohshima KI, Nihashi S, Iwamoto K (2016) Global view of sea-ice production in polynyas and its linkage to dense/bottom water formation. Geosci Lett 3:1–14

Olsson O, North AW (1997) Diet of the king penguin *Aptenodytes patagonicus* during three summers at South Georgia. Ibis 139:504–512. https://doi.org/10.1111/j.1474-919X.1997.tb04666.x

Orheim O, Hagen JO, Østerhus S, Saetrang AC (1990) Studies on, and underneath, the ice shelf Fimbulisen. Norwegian Polar Institute, Oslo

Orsi AH, Johnson GC, Bullister JL (1999) Circulation, mixing, and production of Antarctic bottom water. Prog Oceanogr 43:55–109. https://doi.org/10.1016/S0079-6611(99)00004-X

Pakhomov EA (1998) Diet of two Antarctic dragonfish (Pisces: Bathydraconidae) from the indian sector of the Southern Ocean. Antarct Sci 10:55–61. https://doi.org/10.1017/s095410209800008x

Pakhomov EA (2004) Salp/krill interactions in the eastern Atlantic sector of the Southern Ocean. Deep-Sea Res Part II 51:2645–2660. https://doi.org/10.1016/j.dsr2.2001.03.001

Pakhomov EA, Froneman PW (2004) Zooplankton dynamics in the eastern Atlantic sector of the Southern Ocean during the austral summer 1997/1998 - Part 2: Grazing impact. Deep-Sea Res Part II 51:2617–2631. https://doi.org/10.1016/j.dsr2.2000.11.002

Pakhomov EA, Perissinotto R, McQuaid CD (1996) Prey composition and daily rations of myctophid fishes in the Southern Ocean. Mar Ecol Prog Ser 134:1–14. https://doi.org/10.3354/meps134001

Pakhomov EA, Perissinotto R, Froneman PW (1998) Abundance and trophodynamics of *Euphausia crystallorophias* in the shelf region of the Lazarev Sea during austral spring and summer. J Mar Syst 17:313–324

Pakhomov EA, Perissinotto R, McQuaid CD, Froneman PW (2000) Zooplankton structure and grazing in the Atlantic sector of the Southern Ocean in late austral summer 1993. Part 1. Ecological zonation. Deep Sea Res Part 1 Oceanogr Res Pap 47:1663–1686. https://doi.org/10.1016/S0967-0637(99)00122-3

Paolo FS, Fricker HA, Padman L (2015) Volume loss from Antarctic ice shelves is accelerating. Science 348:327–331. https://doi.org/10.1126/science.aaa0940

Pattyn F, Matsuoka K, Callens D et al (2012) Melting and refreezing beneath Roi Baudouin Ice Shelf (East Antarctica) inferred from radar, GPS, and ice core data. J Geophys Res Earth Surf. https://doi.org/10.1029/2011JF002154

Pfaffhuber KA, Berg T, Hirdman D, Stohl A (2012) Atmospheric mercury observations from Antarctica: seasonal variation and source and sink region calculations. Atmos Chem Phys 12:3241–3251. https://doi.org/10.5194/acp-12-3241-2012

Phartiyal B, Sharma A, Bera SK (2011) Glacial lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica, during Late Quaternary. Quat Int 235:128–136. https://doi.org/10.1016/j.quaint.2010.11.025

Philippe M, Tison JL, Fjøsne K et al (2016) Ice core evidence for a 20th century increase in surface mass balance in coastal Dronning Maud Land, East Antarctica. Cryosphere 10:2501–2516. https://doi.org/10.5194/tc-10-2501-2016

Piatkowski U, Pütz K (1994) Squid diet of emperor penguins (*Aptenodytes forsteri*) in the eastern Weddell Sea, Antarctica during late summer. Antarct Sci 6:241–247. https://doi.org/10.1017/S0954102094000374

Pineda-Metz SEA, Isla E, Gerdes D (2019) Benthic communities of the Filchner Region (Weddell Sea, Antarctica). Mar Ecol Prog Ser 628:37–54. https://doi.org/10.3354/meps13093

Pineda-Metz SEA, Gerdes D, Richter C (2020) Benthic fauna declined on a whitening Antarctic continental shelf. Nat Commun. https://doi.org/10.1038/s41467-020-16093-z

Pinkerton MH, Bradford-Grieve JM, Hanchet SM (2010a) A balanced model of the food web of the Ross Sea, Antarctica. CCAMLR Sci 17:1–31

Pinkerton MH, Smith ANH, Raymond B et al (2010b) Spatial and seasonal distribution of adult Oithona similis in the Southern Ocean: predictions using boosted regression trees. Deep Sea Res Part 1 Oceanogr Res Pap 57:469–485. https://doi.org/10.1016/j.dsr.2009.12.010

Pirli M, Matsuoka K, Schweitzer J, Moholdt G (2015) Seismic signals from large, tabular icebergs drifting along the Dronning Maud Land coast, Antarctica, and their significance for iceberg monitoring. J Glaciol 61:481–492. https://doi.org/10.3189/2015JoG14J210

Pitcher TJ, Morato T, Hart PJB et al (2008) Seamounts ecology fisheries & conservation. Wiley, Hoboken

Plötz J, Plotz J, Plötz J (1986) Summer diet of Weddell seals (*Leptonychotes weddellii*) in the eastern and southern Weddell Sea, Antarctica. Polar Biol 6:97–102. https://doi.org/10.1007/BF00258259

Plötz J, Ekau W, Reijnders PJH (1991a) Diet of Weddell Seals *Leptonychotes weddellii* at Vestkapp, eastern Weddell Sea) Antarctica, in relation to local food supply. Mar Mamm Sci 7:136–144. https://doi.org/10.1111/j.1748-7692.1991.tb00560.x

Plötz J, Weidel H, Bersch M et al (1991b) Winter aggregations of marine mammals and birds in the north-eastern Weddell Sea pack ice. Polar Biol 11:305–309. https://doi.org/10.1007/BF00239022

Plötz J, Bornemann H, Knust R et al (2002) Foraging behaviour of Weddell seals, and its ecological implications. Ecological studies in the Antarctic sea ice zone. Springer, Berlin Heidelberg, pp 148–156

Poulin E, Palma AT, Feéral JP (2002) Evolutionary versus ecological success in Antarctic benthic invertebrates. Trends Ecol Evol 17:218–222

Pratap B, Dey R, Matsuoka K et al (2022) Three-decade spatial patterns in surface mass balance of the Nivlisen Ice Shelf, central Dronning Maud Land, East Antarctica. J Glaciol 68:174–186. https://doi.org/10.1017/jog.2021.93

Pretorius WB, Das S, Monteiro PMS (2014) Investigating the complex relationship between in situ Southern Ocean pCO_2 and its ocean physics and biogeochemical drivers using a nonparametric regression approach. Environ Ecol Stat 21:697–714. https://doi.org/10.1007/s10651-014-0276-5

Price MR, Heywood KJ, Nicholls KW (2007) Ice-shelf – ocean interactions at Fimbul Ice Shelf, Antarctica from oxygen isotope ratio measurements. Ocean Sci Discuss 4:709–732. https://doi.org/10.5194/osd-4-709-2007

Priddle J, Whitehouse MJ, Ward P et al (2003) Biogeochemistry of a Southern Ocean plankton ecosystem: using natural variability in community composition to study the role of metazooplankton in carbon and nitrogen cycles. J Geophys Res. https://doi.org/10.1029/2000jc000425

Pritchard HD, Ligtenberg SRM, Fricker HA et al (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature 484:502–505. https://doi.org/10.1038/nature10968

Raguá-Gil JM, Gutt J, Clarke A, Arntz WE (2004) Antarctic shallow-water mega-epibenthos: shaped by circumpolar dispersion or local conditions? Mar Biol 144:829–839. https://doi.org/10.1007/s00227-003-1269-3

Rau GH, Ainley DG, Bengtson JL et al (1992) 15N/14N and 13C/12C in Weddell Sea birds, seals, and fish: implications for diet and trophic structure. Mar Ecol Prog Ser 84:1–8

Raymond B, Lea MA, Patterson T et al (2015) Important marine habitat off east Antarctica revealed by two decades of multi-species predator tracking. Ecography 38:121–129. https://doi.org/10.1111/ecog.01021

Reeve KA, Boebel O, Strass V et al (2019) Horizontal circulation and volume transports in the Weddell Gyre derived from Argo float data. Prog Oceanogr 175:263–283. https://doi.org/10.1016/j.pocean.2019.04.006

Reeves RR, Hofman RJ, Silber GK, Wilkinson D (1996) Acoustic deterrence of harmful marine mammal-fishery interactions. In: Proceedings of a workshop held in Seattle, Washington, 20–22 Mar 1996

Riaux-Gobin C, Poulin M, Prodon R, Treguer P (2003) Land-fast ice microalgal and phytoplanktonic communities (Adélie Land, Antarctica) in relation to environmental factors during ice break-up. Antarct Sci 15:353–364. https://doi.org/10.1017/S0954102003001378

Rignot E, Jacobs S, Mouginot J, Scheuchl B (2013) Ice-shelf melting around Antarctica. Science 341:266–270. https://doi.org/10.1126/science.1235798

Robinson DH, Kolber Z, Sullivan CW (1997) Photophysiology and photoacclimation in surface sea ice algae from McMurdo Sound, Antarctica. Mar Ecol Prog Ser 147:243–256. https://doi.org/10.3354/meps147243

Rodhouse PG, Clarke MR (1986) Distribution of the early-life phase of the Antarctic squid *Galiteuthis glacialis* in relation to the hydrology of the Southern Ocean in the sector 15° to 30°E. Mar Biol 91:353–357. https://doi.org/10.1007/BF00428629

Rodhouse PG, White MG (1995) Cephalopods occupy the ecological niche of epipelagic fish in the Antarctic Polar Frontal Zone. Biol Bull 189:77–80. https://doi.org/10.2307/1542457

Rodhouse PG, Clarke MR, Murray AWAA (1987) Cephalopod prey of the wandering albatross *Diomedea exulans*. Mar Biol 96:1–10. https://doi.org/10.1007/BF00394833

Rodhouse PG, Prince PA, Clarke MR, Murray AWA (1990) Cephalopod prey of the grey-headed albatross *Diomedea chrysostoma*. Mar Biol 104:353–362. https://doi.org/10.1007/BF01314337

Roeser HA, Fritsch J, Hinz K (1996) The development of the crust off Dronning Maud Land, East Antarctica. Geol Soc Lond 108:243–264. https://doi.org/10.1144/GSL.SP.1996.108.01.18

Ropert-Coudert Y, Hindell MA, Phillips RA et al (2014) Biogeographic patterns of birds and mammals. In: De Broyer C, Koubbi P, Griffiths HJ et al (eds) Biogeographic atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, pp 364–387

Roquet F, Wunsch C, Forget G et al (2013) Estimates of the Southern Ocean general circulation improved by animal-borne instruments. Geophys Res Lett 40:6176–6180. https://doi.org/10.1002/2013GL058304

Roukaerts A, Deman F, Van der Linden F et al (2021) The biogeochemical role of a microbial biofilm in sea ice. Elementa 9:00134. https://doi.org/10.1525/elementa.2020.00134

Ryan PG, Watkins BP (1988) Birds of the island mountains of western Dronning Maud Land, Antarctica. Cormorant 16:34–40

Ryan S, Schröder M, Huhn O, Timmermann R (2016) On the warm inflow at the eastern boundary of the Weddell Gyre. Deep Sea Res Part 1 Oceanogr Res Pap 107:70–81. https://doi.org/10.1016/j.dsr.2015.11.002

Sabine CL, Feely RA, Gruber N et al (2004) The oceanic sink for anthropogenic CO_2. Science 305:367–371. https://doi.org/10.1126/science.1097403

Sabine CL, Hankin S, Koyuk H et al (2013) Surface Ocean CO2 Atlas (SOCAT) gridded data products. Earth Syst Sci Data 5:145–153. https://doi.org/10.5194/essd-5-145-2013

Sallée JB, Matear RJ, Rintoul SR, Lenton A (2012) Localized subduction of anthropogenic carbon dioxide in the Southern Hemisphere oceans. Nat Geosci 5:579–584. https://doi.org/10.1038/ngeo1523

Sauter D, Cannat M, Rouméjon S et al (2013) Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years. Nat Geosci 6:314–320. https://doi.org/10.1038/ngeo1771

Scambos TA, Hulbe C, Fahnestock M, Bohlander J (2000) The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. J Glaciol 46:516–530. https://doi.org/10.3189/172756500781833043

Schaafsma FL, Cherel Y, Flores H et al (2018) Review: the energetic value of zooplankton and nekton species of the Southern Ocean. Mar Biol 165:1–35

Schaffer J, Timmermann R, Erik Arndt J et al (2016) A global, high-resolution data set of ice sheet topography, cavity geometry, and ocean bathymetry. Earth Syst Sci Data 8:543–557. https://doi.org/10.5194/essd-8-543-2016

Schall E, Thomisch K, Boebel O et al (2020) Large-scale spatial variabilities in the humpback whale acoustic presence in the Atlantic sector of the Southern Ocean. R Soc Open Sci 7:201347. https://doi.org/10.1098/rsos.201347

Scheidat M, Friedlaender A, Kock KH et al (2011) Cetacean surveys in the Southern Ocean using icebreaker-supported helicopters. Polar Biol 34:1513–1522. https://doi.org/10.1007/s00300-011-1010-5

Schmidt K, Atkinson A, Steigenberger S et al (2011) Seabed foraging by antarctic krill: implications for stock assessment, bentho-pelagic coupling, and the vertical transfer of iron.

Limnol Oceanogr 56:1411–1428. https://doi.org/10.4319/lo.2011.56.4.1411

Schmidt K, Atkinson A, Pond DW, Irel LC (2014) Feeding and overwintering of antarctic krill across its major habitats: the role of sea ice cover, water depth, and phytoplankton abundance. Limnol Oceanogr 59:17–36. https://doi.org/10.4319/lo.2014.59.1.0017

Schumacher U, Rauh G, Piötz J, Welsch U (1992) Basic biochemical data on blood from antarctic Weddell seals (*Leptonychotes weddellii*): ions, lipids, enzymes, serum proteins and thyroid hormones. Comp Biochem Physiol Part A 102:449–451. https://doi.org/10.1016/0300-9629(92)90192-S

Shabangu FW, Findlay K, Stafford KM (2020) Seasonal acoustic occurrence, diel-vocalizing patterns and bioduck call-type composition of Antarctic minke whales off the west coast of South Africa and the Maud Rise, Antarctica. Mar Mamm Sci 36:658–675. https://doi.org/10.1111/mms.12669

Sharp BR, Parker SJ, Pinkerton MH, et al (2010) Bioregionalisation and spatial ecosystem processes in the Ross Sea region. Working Groupon Ecosystem Monitoring and Management-10/30. Commission for the Conservation ofAntarctic Marine Living Resources

Shevenell AE, Ingalls AE, Domack EW, Kelly C (2011) Holocene Southern Ocean surface temperature variability west of the Antarctic Peninsula. Nature 470:250–254. https://doi.org/10.1038/nature09751

Siegel V (2005) Distribution and population dynamics of *Euphausia superba*: summary of recent findings. Polar Biol 29:1–22. https://doi.org/10.1007/s00300-005-0058-5

Siegel V (2012) Krill stocks in high latitudes of the Antarctic Lazarev Sea: seasonal and interannual variation in distribution, abundance and demography. Polar Biol 35:1151–1177. https://doi.org/10.1007/s00300-012-1162-y

Siegel V, Loeb V (1995) Recruitment of Antarctic krill *Euphausia superba* and possible causes for its variability. Mar Ecol Prog Ser 123:45–56. https://doi.org/10.3354/meps123045

International Hydrographic Organization IHO, Sieger R (2012) Limits of oceans and seas in digitized, machine readable form

Sinisalo A, Anschütz H, Langley K et al (2013) Surface mass balance on Fimbul ice shelf, East Antarctica: comparison of field measurements and large-scale studies. J Geophys Res Atmos 118:11625–11635. https://doi.org/10.1002/jgrd.50875

Skinner JD, Klages NTWW (1994) On some aspects of the biology of the Ross seal *Ommatophoca rossii* from King Haakon VII Sea, Antarctica. Polar Biol 14:467–472. https://doi.org/10.1007/BF00239051

Smedsrud LH, Jenkins A, Holland DM, Nøst OA (2006) Modeling ocean processes below Fimbulisen, Antarctica. J Geophys Res. https://doi.org/10.1029/2005JC002915

Smetacek V, Scharek R, Gordon LI et al (1992) Early spring phytoplankton blooms in ice platelet layers of the southern Weddell Sea, Antarctica. Deep Sea Res Part A 39:153–168. https://doi.org/10.1016/0198-0149(92)90102-Y

Smetacek V, De Baar HJW, Bathmann UV et al (1997) Ecology and biogeochemistry of the Antarctic circumpolar current during austral spring: a summary of Southern Ocean JGOFS cruise ANT X/6 of R.V. Polarstern. Deep-Sea Res Part II 44:1–21. https://doi.org/10.1016/S0967-0645(96)00100-2

Smetacek V, Klaas C, Menden-Deuer S, Rynearson TA (2002) Mesoscale distribution of dominant diatom species relative to the hydrographical field along the Antarctic Polar Front. Deep-Sea Res Part II 49:3835–3848. https://doi.org/10.1016/S0967-0645(02)00113-3

Smith B, Fricker HA, Gardner AS et al (2020) Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. Science 275:eaaz5845. https://doi.org/10.1126/science.aaz5845

Southwell C, Bengtson J, Bester M et al (2012) A review of data on abundance, trends in abundance, habitat use and diet of ice-breeding seals in the Southern Ocean. CCAMLR Sci 19:1–26

Spicer JI, Morley SA (2019) Will giant polar amphipods be first to fare badly in an oxygen-poor ocean? Testing hypotheses linking oxygen to body size. Philos Trans R Soc B. https://doi.org/10.1098/rstb.2019.0034

Spindler M (1994) Notes on the biology of sea ice in the Arctic and Antarctic. Polar Biol 14:319–324. https://doi.org/10.1007/BF00238447

Stammerjohn S, Massom R, Rind D, Martinson D (2012) Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. Geophys Res Lett. https://doi.org/10.1029/2012GL050874

Steinhagen-Schneider G (1986) Cadmium and copper levels in seals, penguins and skuas from the Weddell Sea in 1982/1983. Polar Biol 5:139–143. https://doi.org/10.1007/BF00441693

Stenni B, Buiron D, Frezzotti M et al (2011) Expression of the bipolar see-saw in Antarctic climate records during the last deglaciation. Nat Geosci 4:46–49. https://doi.org/10.1038/ngeo1026

Stenni B, Curran MAJ, Abram NJ et al (2017) Antarctic climate variability on regional and continental scales over the last 2000 years. Climate past 13:1609–1634. https://doi.org/10.5194/cp-13-1609-2017

Stenvers O, Plötz J, Ludwig H (1992) Antarctic seals carry antibodies against seal herpesvirus. Adv Virol 123:421–424. https://doi.org/10.1007/BF01317275

Stewart AL, Thompson AF (2015) Eddy-mediated transport of warm Circumpolar Deep Water across the Antarctic Shelf Break. Geophys Res Lett 42:432–440. https://doi.org/10.1002/2014GL062281

St-Laurent P, Klinck JM, Dinniman MS (2013) On the role of coastal troughs in the circulation of warm circumpolar deep water on Antarctic shelves. J Phys Oceanogr 43:51–64. https://doi.org/10.1175/JPO-D-11-0237.1

Stoll MHC, DE Baar HJW, Hoppema M, Fahrbach E (1999) New early winter fCO$_2$ data reveal continuous uptake of CO$_2$ by the Weddell Sea. Tellus B 51:679–687. https://doi.org/10.1034/j.1600-0889.1999.t01-2-00008.x

Sugimoto F, Tamura T, Shimoda H et al (2016) Interannual variability in sea-ice thickness in the pack-ice zone off Lützow-Holm Bay, East Antarctica. Polar Sci 10:43–51. https://doi.org/10.1016/j.polar.2015.10.003

Sun S, Hattermann T, Pattyn F et al (2019) Topographic shelf waves control seasonal melting near Antarctic ice shelf grounding lines. Geophys Res Lett 46:9824–9832. https://doi.org/10.1029/2019GL083881

Sverdrup HU (1954) The currents off the coast of queen maud land. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 14:239–249. https://doi.org/10.1080/00291955308542731

Swadling KM, Kawaguchi S, Hosie GW (2010) Antarctic meso-zooplankton community structure during BROKE-West (30°E-80°E), January-February 2006. Deep-Sea Res Part II 57:887–904. https://doi.org/10.1016/j.dsr2.2008.10.041

Swithinbank C (1969) Giant icebergs in the Weddell Sea, 1967–68. Polar Rec 14:477–478. https://doi.org/10.1017/S0032247400064500

Sylvester ZT, Brooks CM (2020) Protecting Antarctica through Co-production of actionable science: lessons from the CCAMLR marine protected area process. Mar Policy 111:103720. https://doi.org/10.1016/j.marpol.2019.103720

Tagliabue A, Sallée JB, Bowie AR et al (2014) Surface-water iron supplies in the Southern Ocean sustained by deep winter mixing. Nat Geosci 7:314–320. https://doi.org/10.1038/ngeo2101

Takahashi T, Sutherland SC, Wanninkhof R et al (2009) Climatological mean and decadal change in surface ocean pCO$_2$, and net

sea-air CO_2 flux over the global oceans. Deep-Sea Res Part II 56:554–577. https://doi.org/10.1016/j.dsr.2008.12.009

Talley LD (2013) Closure of the global overturning circulation through the Indian, Pacific, and southern oceans. Oceanography 26:80–97. https://doi.org/10.5670/oceanog.2013.07

Tamura T, Ohshima KI, Fraser AD, Williams GD (2016) Sea ice production variability in Antarctic coastal polynyas. J Geophys Res 121:2967–2979. https://doi.org/10.1002/2015JC011537

Tarling GA, Fielding S (2016) Swarming and behaviour in Antarctic krill. In: Siegel V (ed) Biology and ecology of Antarctic krill. Springer, Cham, pp 279–319

Tarroux A, Cherel Y, Fauchald P et al (2020) Foraging tactics in dynamic sea-ice habitats affect individual state in a long-ranging seabird. Funct Ecol 34:1839–1856. https://doi.org/10.1111/1365-2435.13632

Tavares M, De Melo GAS (2004) Discovery of the first known benthic invasive species in the Southern Ocean: the North Atlantic spider crab *Hyas araneus* found in the Antarctic Peninsula. Antarct Sci 16:129–131. https://doi.org/10.1017/S0954102004001877

Taylor F, Whitehead J, Domack E (2001) Holocene paleoclimate change in the Antarctic Peninsula: evidence from the diatom, sedimentary and geochemical record. Mar Micropaleontol 41:25–43. https://doi.org/10.1016/S0377-8398(00)00049-9

Terhune JM, Quin D, Dell'Apa A et al (2008) Geographic variation in underwater male Weddell seal trills suggest breeding area fidelity. Polar Biol 31:671–680. https://doi.org/10.1007/s00300-008-0405-4

Teschke K, Brtnik P, Hain S et al (2021) Planning marine protected areas under the CCAMLR regime: the case of the Weddell Sea (Antarctica). Mar Policy 124:104370

Teschke K, Pehlke H, VS-ES (2020) U An integrated compilation of data sources for the development of a marine protected area in the Weddell Sea. essd.copernicus.org

Thiede J, Oerter H (2002) Die Expedition ANTARKTIS XVII/2 des Forschungsschiffes POLARSTERN 2000 = The expedition ANTARKTIS XVII/2 of the research vessel POLARSTERN in 2000. In: Berichte zur Polar- und Meeresforschung (Reports on Polar and Marine Research). https://epic.awi.de/id/eprint/26583/%0Afile:///media/pim/myhre-feltarabeid/NettNpolarMyhre/bibliotek/storage/CRZ84VCX/26583.html

Thomas ER, Allen CS, Etourneau J et al (2019) Antarctic sea ice proxies from marine and ice core archives suitable for reconstructing sea ice over the past 2000 years. Geosciences (switzerland) 9:506

Thomisch K, Boebel O, Clark CW et al (2016) Spatio-temporal patterns in acoustic presence and distribution of Antarctic blue whales *Balaenoptera musculus* intermedia in the Weddell Sea. Endanger Species Res 30:239–253. https://doi.org/10.3354/esr00739

Thompson AF, Stewart AL, Spence P, Heywood KJ (2018) The Antarctic slope current in a changing climate. Rev Geophys 56:741–770. https://doi.org/10.1029/2018RG000624

Timmermann R, Goeller S (2017) Response to Filchner-Ronne Ice Shelf cavity warming in a coupled ocean-ice sheet model - Part 1: the ocean perspective. Ocean Sci 13:765–776. https://doi.org/10.5194/os-13-765-2017

Tison JL, Schwegmann S, Dieckmann G, Rintala JM, Meyer H, Moreau S, Delille B (2017) Biogeochemical impact of snow cover and cyclonic intrusions on the winter Weddell Sea ice pack. J Geophys Res 122(12):9548–9571

Trathan PN, Grant SM (2019) The South Orkney Islands Southern Shelf Marine Protected Area : towards the establishment of marine spatial protection within international waters in the Southern Ocean. In: Marine Protected Areas. pp 67–98

Trusel LD, Frey KE, Das SB et al (2013) Satellite-based estimates of Antarctic surface meltwater fluxes. Geophys Res Lett 40:6148–6153. https://doi.org/10.1002/2013GL058138

Tryland M, Klein J, Nordøy ES, Blix AS (2005) Isolation and partial characterization of a parapoxvirus isolated from a skin lesion of a Weddell seal. Virus Res 108:83–87. https://doi.org/10.1016/j.virusres.2004.08.005

Tryland M, Nymo IH, Nielsen O et al (2012) Serum chemistry and antibodies against pathogens in antarctic fur seals, Weddell seals, crabeater seals, and Ross seals. J Wildl Dis 48:632–645. https://doi.org/10.7589/0090-3558-48.3.632

Uto S, Shimoda H, Ushio S (2006) Characteristics of sea-ice thickness and snow-depth distributions of the summer landfast ice in Lützow-Holm Bay, East Antarctica. Ann Glaciol 44:281–287

Van De Putte A, Flores H, Volckaert F, Van Franeker JA (2006) Energy content of Antarctic mesopelagic fishes: implications for the marine food web. Polar Biol 29:1045–1051. https://doi.org/10.1007/s00300-006-0148-z

Van de Putte AP, Jackson GD, Pakhomov E et al (2010) Distribution of squid and fish in the pelagic zone of the Cosmonaut Sea and Prydz Bay region during the BROKE-West campaign. Deep-Sea Res Part II 57:956–967. https://doi.org/10.1016/j.dsr2.2008.02.015

Van Opzeeland I, Hillebrand H (2020) Year-round passive acoustic data reveal spatiotemporal patterns in marine mammal community composition in the Weddell Sea, Antarctica. Mar Ecol Prog Ser 638:191–206. https://doi.org/10.3354/meps13258

Van Franeker JA, Gavrilo M, Mehlum F et al (1999) Distribution and abundance of the Antarctic Petrel. Waterbirds 22:14–28. https://doi.org/10.2307/1521989

Van Heuven SMAC, Hoppema M, Jones EM, De Baar HJW (2014) Rapid invasion of anthropogenic CO2 into the deep circulation of the Weddell Gyre. Philos Trans R Soc A Math Phys Eng Sci. https://doi.org/10.1098/rsta.2013.0056

Van Leeuwe MA, Tedesco L, Arrigo KR et al (2018) Microalgal community structure and primary production in Arctic and Antarctic sea ice: a synthesis. Elementa 6:4

Van Opzeeland I, Van Parijs S, Bornemann H et al (2010) Acoustic ecology of antarctic pinnipeds. Mar Ecol Prog Ser 414:267–291

Vause BJ, Morley SA, Fonseca VG et al (2019) Spatial and temporal dynamics of Antarctic shallow soft-bottom benthic communities: ecological drivers under climate change. BMC Ecol. https://doi.org/10.1186/s12898-019-0244-x

Vernet M, Martinson D, Iannuzzi R et al (2008) Primary production within the sea-ice zone west of the Antarctic Peninsula: I-Sea ice, summer mixed layer, and irradiance. Deep-Sea Res Part II 55:2068–2085. https://doi.org/10.1016/j.dsr2.2008.05.021

Vernet M, Geibert W, Hoppema M et al (2019) The Weddell Gyre, Southern Ocean: present knowledge and future challenges. Rev Geophys 57:623–708. https://doi.org/10.1029/2018RG000604

Vetter W, Luckas B (2000) Enantioselective determination of persistent and partly degradable toxaphene congeners in high trophic level biota. Chemosphere 41:499–506. https://doi.org/10.1016/S0045-6535(99)00478-6

Vetter W, Weichbrodt M, Stoll E (2003) Indication of geographic variations of organochlorine concentrations in the blubber of Antarctic Weddell seals (*Leptonychotes weddellii*). Environ Sci Technol 37:840–844. https://doi.org/10.1021/es025949v

Vetter W, Krock B, Luckas B (1997) Congener specific determination of compounds of technical toxaphene (CTTs) in different Antarctic seal species. Chromatographia 44:65–73

Vinje TE (1977) Drift av Troltunga i Weddellhavet. Årbok 1975. Norsk Polarinstitutt, Oslo

von Harbou L, Dubischar CD, Pakhomov EA et al (2011) Salps in the Lazarev Sea, Southern Ocean: I feeding dynamics. Mar Biol 158:2009–2026. https://doi.org/10.1007/s00227-011-1709-4

Voronina NM (1998) Comparative abundance and distribution of major filter-feeders in the Antarctic Pelagic Zone. J Mar Syst 17:375–390

Watanabe Y, Bornemann H, Liebsch N et al (2006) Seal-mounted cameras detect invertebrate fauna on the underside of an Antarctic ice shelf. Mar Ecol Prog Ser 309:297–300

Watanuki Y, Mori Y, Naito Y (1994) *Euphausia superba* dominates in the diet of Adélie penguins feeding under fast sea-ice in the shelf areas of Enderby Land in summer. Polar Biol 14:429–432. https://doi.org/10.1007/BF00240264

Weimerskirch H, Tarroux A, Chastel O et al (2015) Population-specific wintering distributions of adult south polar skuas over three oceans. Mar Ecol Prog Ser 538:229–237. https://doi.org/10.3354/meps11465

Welsford DC (2011) Evaluating the impact of multi-year research catch limits on overfished toothfish populations. CCAMLR Sci 18:47–55

Wenzel L, Gilbert N, Goldsworthy L et al (2016) Polar opposites? Marine conservation tools and experiences in the changing Arctic and Antarctic. Aquat Conserv Mar Freshwat Ecosyst 26:61–84. https://doi.org/10.1002/aqc.2649

White MG, Piatkowski U (1993) Abundance, horizontal and vertical distribution of fish in eastern Weddell Sea micronekton. Polar Biol 13:41–53. https://doi.org/10.1007/BF00236582

Williams R, Kelly N, Boebel O et al (2014) Counting whales in a challenging, changing environment. Sci Rep. https://doi.org/10.1038/srep04170

Winther J-G, Elvehøy H, Bøggild CE et al (1996) Melting, runoff and the formation of frozen lakes in a mixed snow and blue-ice field in Dronning Maud Land, Antarctica. J Glaciol 42:271–278. https://doi.org/10.3189/s0022143000004135

Wohlschlag DE, DeWitt HH (1972) Coastal and deep-water benthic fishes of the Antarctic. Copeia 1972:902. https://doi.org/10.2307/1442768

Wöhrmann APA, Zimmermann C (1992) Fischereibiologische Untersuchungen während der Polarstern-Expedition ANT IX/3 (3.1.-28.3. 91) in das Weddellmeer und das Lazarevmeer. Mitteilungen Zur Kieler Polarforschung 7:31–37

Woods HA, Lane SJ, Shishido C et al (2017) Respiratory gut peristalsis by sea spiders. Curr Biol 27:R638–R639

Worby AP, Geiger CA, Paget MJ et al (2008) Thickness distribution of Antarctic sea ice. J Geophys Res. https://doi.org/10.1029/2007JC004254

Xavier JC, Raymond B, Jones DC, Griffiths H (2016) Biogeography of cephalopods in the southern ocean using habitat suitability prediction models. Ecosystems 19:220–247. https://doi.org/10.1007/s10021-015-9926-1

Xiao W, Esper O, Gersonde R (2016) Last Glacial - Holocene climate variability in the Atlantic sector of the Southern Ocean. Quat Sci Rev 135:115–137. https://doi.org/10.1016/j.quascirev.2016.01.023

Yamashita R, Takada H, Nakazawa A et al (2018) Global monitoring of persistent organic pollutants (POPs) using seabird preen gland oil. Arch Environ Contam Toxicol 75:545–556. https://doi.org/10.1007/s00244-018-0557-3

Yi D, Zwally HJ, Robbins JW (2011) ICESat observations of seasonal and interannual variations of sea-ice freeboard and estimated thickness in the Weddell Sea, Antarctica (2003–2009). Ann Glaciol 52:43–51. https://doi.org/10.3189/172756411795931480

Zhou Q, Hattermann T, Nøst OA et al (2014) Wind-driven spreading of fresh surface water beneath ice shelves in the Eastern Weddell Sea. J Geophys Res 119:3818–3833. https://doi.org/10.1002/2013JC009556

Authors and Affiliations

Andrew Lowther[1] · **Cecilie von Quillfeldt[1]** · **Philipp Assmy[1]** · **Laura De Steur[1]** · **Sebastien Descamps[1]** · **Dmitry Divine[1]** · **Synnøve Elvevold[1]** · **Matthias Forwick[2]** · **Agneta Fransson[1]** · **Alexander Fraser[3]** · **Sebastian Gerland[1]** · **Mats Granskog[1]** · **Ingeborg Hallanger[1]** · **Tore Hattermann[1]** · **Mikhail Itkin[1]** · **Haakon Hop[1]** · **Katrine Husum[1]** · **Kit Kovacs[1]** · **Christian Lydersen[1]** · **Kenichi Matsuoka[1]** · **Arto Miettinen[4]** · **Geir Moholdt[1]** · **Sebastien Moreau[1]** · **Per Inge Myhre[1]** · **Lisa Orme[5]** · **Olga Pavlova[1]** · **Ann Helene Tandberg[6]**

Cecilie von Quillfeldt
cecilie.von.quillfeldt@npolar.no

Philipp Assmy
philipp.assmy@npolar.no

Laura De Steur
laura.de.steur@npolar.no

Sebastien Descamps
sebastien.descamps@npolar.no

Dmitry Divine
divine@npolar.no

Synnøve Elvevold
elvevold@npolar.no

Matthias Forwick
mattias.forwick@uit.no

Agneta Fransson
agneta.fransson@npolar.no

Alexander Fraser
alexander.fraser@utas.edu.au

Sebastian Gerland
sebastian.gerland@npolar.no

Mats Granskog
mats.granskog@npolar.no

Ingeborg Hallanger
ingeborg.hallanger@npolar.no

Tore Hattermann
tore.hattermann@npolar.no

Mikhail Itkin
mikhail.itkin@npolar.no

Haakon Hop
Haakon.Hop@npolar.no

Katrine Husum
katrine.husum@npolar.no

Kit Kovacs
kit.kovacs@npolar.no

Christian Lydersen
Lydersen@npolar.no

Kenichi Matsuoka
kenichi.matsuoka@npolar.no

Arto Miettinen
arto.miettinen@academies.fi

Geir Moholdt
geir.moholdt@npolar.no

Sebastien Moreau
sebastien.moreau@npolar.no

Per Inge Myhre
myhre@npolar.no

Lisa Orme
lisa.orme@mu.ie

Olga Pavlova
olga.pavlova@npolar.no

Ann Helene Tandberg
anne.helene.tandberg@uib.no

1   Norwegian Polar Institute, Tromsø, Norway

2   The Arctic University, Tromsø, Norway

3   Antarctic Gateway Partnership, Institute for Marine
    and Antarctic Studies, University of Tasmania, Hobart,
    Australia

4   University of Helsinki, Helsinki, Finland

5   Maynooth University, Maynooth, Ireland

6   University Museum of Bergen, Bergen, Norway