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# The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment

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## Abstract :

A quantitative assessment of observed and projected environmental changes in the Southern Ocean (SO) with a potential impact on the marine ecosystem shows: (i) large proportions of the SO are and will be affected by one or more climate change processes; areas projected to be affected in the future are larger than areas that are already under environmental stress, (ii) areas affected by changes in sea-ice in the past and likely in the future are much larger than areas affected by ocean warming. The smallest areas (<1% area of the SO) are affected by glacier retreat and warming in the deeper euphotic layer. In the future, decrease in the sea-ice is expected to be widespread. Changes in iceberg impact resulting from further collapse of ice-shelves can potentially affect large parts of shelf and ephemerally in the off-shore regions. However, aragonite undersaturation (acidification) might become one of the biggest problems for the Antarctic marine ecosystem by affecting almost the entire SO. Direct and indirect impacts of various environmental changes to the three major habitats, sea-ice, pelagic and benthos and their biota are complex. The areas affected by environmental stressors range from 33% of the SO for a single stressor, 11% for two and 2% for three, to <1% for four and five overlapping factors. In the future, areas expected to be affected by 2 and 3 overlapping factors are equally large, including potential iceberg changes, and together cover almost 86% of the SO ecosystem.

**Keywords** : acidification, habitats, icebergs, ice-shelves, ozone depletion, sea-ice, warming

## Introduction

Life on Earth including those in the Southern Ocean (SO) has always been shaped by variations in climate (Crame, 1989; Clarke & Crame, 1992, 1997; Gutt *et al.*, 2010; Kaiser *et al.*, 2013). In addition to natural variability, environmental changes since the mid 20th century are considered to result from anthropogenic impacts on climate (IPCC, 2013). For the SO, the discussion of the anthropogenic contribution, particularly the western Antarctic Peninsula (WAP) area is ongoing (Vaughan *et al.,* 2003, Meredith & King, 2005; Turner *et al.,* 2013a). The reduction in stratospheric ozone (the 'ozone hole') over Antarctica as well as an increase in atmospheric greenhouse gas (Solomon, 1999; Thompson & Solomon, 2002; Marshall *et al.,* 2006) have been linked to accelerating and southward displaced Westerly winds with implications to atmospheric circulation and ocean currents, ocean stratification, nutrient transport, and sea-ice variability (Stammerjohn *et al.,* 2008; Steig *et al.,* 2009; Turner *et al.,* 2009a, 2013b; Thompson *et al.,* 2011; Spence *et al.,* 2012; England *et al.,* 2014). Although our knowledge on Antarctic waters' biology is incomplete, these processes will affect the organisms in different ways and varying among sites. Moreover, spatial gradients in the impact of marine habitats, e.g., those affected by changing sea-ice dynamics, and relatively stable areas are steeper than in other parts of the world. Impacts on Antarctic marine life can also result from discrete events, e.g. the occasional upwelling of warm water and the collapse of ice-shelves (Gutt *et al.,* 2011; Dinniman *et al.,* 2012).

Particular efforts have been undertaken to assemble findings on biological responses to climate change (Turner *et al.*, 2009b, 2013a), but did not quantify them. A number of reviews further focused on single processes and on particular organisms or provided overviews, conclusions or concepts (e.g. Clarke *et al.,* 2007; Aronson *et al.*, 2007, 2011; Murphy *et al.,* 2007; Brandt & Gutt, 2011; Gutt *et al.,* 2012; Ingels *et al.,* 2012; Mintenbeck *et al.,* 2012; C.R. Smith *et al.,* 2012a; W.O. Smith *et al.,* 2012; Constable *et al.,* 2014; Brandt *et al.*, in press). Notably, to study cumulative effects of multiple stressors has recently been identified as important and one of the 80 priority questions for future research in Antarctica and the Southern Ocean (Rogers & Laffoley, 2013; Kennicutt *et al.,* 2014a,b) since they have never been studied in detail in the SO, defined as the ocean south of the Polar Front according to Sokolov & Rintoul (2009a).

The effort invested in field studies, experiments, and numerical computations varied between ecosystem components, e.g. between the key stone species Antarctic krill *Euphausia superba* and largely unknown deep-sea animals, charismatic penguins and tiny microbes, predatory crustaceans and squid as well as rarely seen mid-water fish. As a consequence, the awareness of climate-induced ecosystem shifts by scientists, the public and decision makers varies relatively independently of the quality and quantity of the impact itself. An overarching assessment of the magnitude of environmental impacts not only on the ecosystem themselves but also on their goods and services (Rogers *et al.,* 2013), as well as their degree of certainty, such as applied in the IPCC's 5th Assessment Report, Part B: Regional aspects especially polar regions (Larsen *et al.,* 2014), demands comparative approaches across regions, groups of organisms and key ecological processes.

Our aims are to produce: (1) a qualitative compilation and illustration of important climate-induced environmental changes that potentially have an impact on the Antarctic marine ecosystem, sea-ice increase and decrease, ice-shelf disintegration and iceberg effects, warming, ozone depletion in combination with increased UV-B, and acidification; (2) a geo-referenced mapping of these impacts to show where they occur; (3) calculations of the areas affected; (4) a quantification and mapping of areas affected by multiple environmental impacts; (5) a qualitative assessment of the impairment of affected communities, with the magnitude of the disturbance and regional relevance as key performance indicators. The results refer to changes already-observed and projected for the future. Changing iceberg impact was attributed to the future scenarios, independently of whether such changes have started already or are expected to happen in the future since it is assumed that the impact is long lasting, especially on benthic communities. This study complements the Antarctic Climate Change and the Environment report (Turner *et al.*, 2009b; Convey *et al.*, 2010) and its update (Turner *et al.*, 2013a). It can serve as a basis for a risk assessment of endangered Antarctic marine habitats in the context of regionalisation (Grant *et al.,* 2006; Raymond, 2014; Douglass *et al.,* 2014; Gutt *et al.,* 2014) especially when changes reach thresholds, beyond which organisms experience high levels of stress and when habitats experience tipping points.

## Material and methods

Key coupling processes across the inter-related physical and biological domains are depicted in Fig. 1 and discussed in the Supplementary Information (S1). Phenomena are considered if 1) evidence of their existence is available, 2) they have not been observed but assumed to have been happening and 3) they are expected to occur in the future. Relationships among abiotic and biotic factors are coarsely depicted and restricted to those being relevant for the biosphere. The considered environmental components were atmosphere, sea-ice, ocean, ice-sheet and sea-bed. For the biota we considered those living in or at the sea-ice, in the pelagic and benthic zones.

For the quantitative approach the sizes of the areas exposed to climate change and its effects were taken from the literature or areas were redrawn from the references mentioned using Photoshop (CS5; Adobe), including the determination of multiply affected areas, and using ArcMap (ArcGIS Desktop 10.0, ESRI; "South Pole Lambert Azimuthal Equal Area" projection). Results were rounded to steps of 0.01 x $10^6$ $km^2$.

The following sizes have been used: an extension for the SO of 28.47 x $10^6$ $km^2$ to estimate relative sizes of areas, defined as the area South of the Polar Front with mean positions from Sokolov & Rintoul (2009a) of 42.47 x $10^6$ $km^2$, minus the Antarctic continent (12.16 x $10^6$ $km^2$, ArcGIS layers moa-ice), islands (0.21 x $10^6$ $km^2$, ArcGIS layer moa-land) and ice-shelves in 2002 (1.63 x $10^6$ $km^2$, Clarke & Johnston (2003)). Shelf area not covered by ice-shelves represented 2.97 x $10^6$ $km^2$ in 2002 (Clarke & Johnston, 2003). Sea-ice cover of 18.3 x $10^6$ $km^2$ refers to the average maximum extent in September (Comiso, 2010).

Sea-ice covered areas (Comiso, 2000, updated 2012) were determined for separated seasons between 1979 and 2012. Areas of significant changes were considered when changes exceeded a threshold of 0.015 frac/decade, which is similar to the 0.2 frac/decade in 7.6 decades (=0.013 frac/decade) threshold used for the calculation for the future; frac = fraction (values 0-1) of surface covered by sea-ice. Significances were calculated using a 2-sided student's t-test. Season-specific results for observed and projected changes were summed-up to values for the entire year.

Areas for the cumulative occurrence for the 1992-2012 period of >1 Gt iceberg volume per 1° (latitude) x 2° (longitude) with icebergs <3 km length were calculated using their monthly volume from altimeter data analysis (Tournadre *et al.,* 2012), if occurrence was significantly greater than the noise level. This indicates that at least for one month during the period such icebergs have been present. Occurrences of icebergs >5 km were taken from the areas in the plot of iceberg tracks by Stuart & Long (2011, Fig. 9).

Increased UV-B was analysed for the three seasonal periods of the thinning of the ozone layer, referred to here after as the ozone hole, it's full development, it's end, and the beginning summer without, to demonstrate that at the end of the winter the ozone hole is well established but high sea-ice cover allows UV-B to penetrate only into a certain proportion of the ocean and that in December the ozone hole is almost closed. For each of the three periods results for three days from three years were merged to cover a high short- and long-term variability. For November these dates had three replicates to provide information on the representativeness of these results. Ozone maps were used from "Environment Canada" (http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap), based on ground-based measurements with adjustments according to results from satellite probes available from World Ozone and Ultraviolet Radiation Data Centre. Sizes of areas with ≥250 Dobson units and <80% sea-ice cover were determined (ASI Algorithm SSMI-SSMIS sea-ice concentration were obtained from the Integrated Climate Data Centre, University of Hamburg, Germany;

http://icdc.zmaw.de/seaiceconcentration_asi_ssmi.html; Kaleschke *et al.,* 2001; Spreen *et al.,* 2008).

## Results

### *Qualitative compilation*

Interactions between climate-induced physical and chemical changes and the potential response of marine biota of the SO are complex (Fig. 1, S1). All three large habitats, the sea-ice, the pelagic and benthic zones are affected directly by changes in the four major environment components, atmosphere, sea-ice in its extent and season length, ocean, and icesheet. In addition, non-linear, hardly reproducible and complex indirect effects can be important, e.g. if warming of the atmosphere and changes in the wind regime reduce the sea-ice, primary production and population growth of Antarctic krill are affected and, as a further consequence, energy flux to higher trophic levels and to the sea-floor is modified. Another example is the disintegration of ice-shelves, allowing the phytoplankton to develop in areas previously covered by ice, which later in the year sinks to the bottom and changes an oligotrophic to a "normal" Antarctic system.

Quantitative data on ecologically relevance environmental changes are compiled in Table 1; the most relevant results are depicted in Figs 2 to 4.

### *Observed and projected ocean warming*

Physiological experiments show that a warming of 1 K represents a threshold at which organisms start to respond significantly (Barnes & Peck, 2008; Peck*,* 2011; Peck *et al.,* 2014). For this reason, we use the 1K threshold to identify SO regions susceptible to physiological impacts. The area of the western Antarctic Peninsula (WAP) in which an increase $\gtrsim$1.0 K in sea-surface temperature (SST) was observed between 1955 and 1998 (= $\gtrsim$0.023 K p.a.) was 0.73 x $10^6$ km$^2$ based on Meredith & King (2005), which corresponds to 2.6% of the SO (Figs 2a & 4). At 50 m depth, the area of an equivalent warming was only 0.05 x $10^6$ km$^2$. The

WAP is the region considered to have experienced the highest SST-increase in the SO in the past decades. Reports of a similar warming are known from an adjacent site (Schloss *et al.,* 2012). This might be representative of more localities in that area, but warming is not known from other areas of similar extent (see e.g. Gille *et al*., 2002). The length of the Polar Front was calculated as 32,176 km using mean front positions from Sokolov & Rintoul (2009a). Sokolov & Rintoul (2009b) estimated a 60 km southward shift between 1992 and 2007 with $\leq$ 2 K south and $\geq$ 4-5 K north of it, so that the area affected by this warming was 1.93 x $10^6$ $km^2$, which is 6.8% of the SO (Figs 2a & 4).

A projection of SST until 2100 shows a warming of >1 K along the northern margin of the SO (Turner *et al.*, 2009b), which would affect an area year-round of 5.87 x $10^6$ $km^2$ (Figs 3a & 4) representing 20.6% of the SO, 3.26 x $10^6$ $km^2$ in summer and 4.35 x $10^6$ $km^2$ in winter. At 200 m depth the area of an equivalent warming was 0.78 x $10^6$ $km^2$, representing 2.8% of the SO, 0.50 x $10^6$ $km^2$ in summer and 0.64 x $10^6$ $km^2$ in winter.

*Observed changes in sea-ice season length and extent*

The area affected by an increase in the length of the sea-ice season (1979 - 1999) was calculated as 2.68 x $10^6$ $km^2$, whereas the area of decrease was 1.15 x $10^6$ $km^2$. A 15% ice-concentration cut-off and zeroing out trends with < 95% confidence level (Parkinson, 2002; Fig. 2b) was applied. These values are equivalent to 34% and 15% area, respectively, relative to the average annual sea-ice area of 7.9 x $10^6$ $km^2$ (Bracegirdle *et al.,* 2008) or 15% and 6%, respectively, to the maximum sea-ice extent of 18.3 x $10^6$ $km^2$ (Fig. 4).

Areas of significant change in sea-ice extent (1979-2012) vary between seasons from 0.42 to 1.08 x $10^6$ $km^2$ increase and from 0.06 to 0.58 x $10^6$ $km^2$ decrease (Table 1 and Fig. 2b). Decrease was highest in summer in the WAP area and Amundsen/Bellingshausen Seas. Increases were observed in the Ross and Weddell Seas as well as in the Indian sector of the

SO, which were least obvious in autumn. Merged values from the seasonal data for the entire year result in a 6.06 x $10^6$ $km^2$ increase and 1.55 x $10^6$ $km^2$ decrease, which is 33% increase and 9% decrease relative to the yearly average sea-ice cover. Areas of any change were 7.61 x $10^6$ $km^2$ and affected 42% of the maximum sea-ice extent. Values for the annual mean (ANN) are similar.

*Projected sea-ice area change*

The projection of annual average sea-ice area change between 2004/2023 and 2080/2099 calculated by Bracegridle *et al.* (2008) is a decrease of 2.6 x $10^6$ $km^2$, which is 33% of the annual average ice-covered area before the 21st century and 14% of its maximum winter sea-ice extent (Fig. 4). Most of this decrease is expected for June to November. If a threshold of 0.1 frac/7.6decade of the sea-ice concentration is applied similar to the 0.02 frac/decade for the past, the year-round affected area is 15.1 x $10^6$ $km^2$, which is 83% of the maximum sea-ice extent (Fig. 3b).

*Ice-shelf disintegration and icebergs*

The area of ice-shelves collapsed since the 1960s associated with atmosphere and ocean warming east and west of the Antarctic Peninsula is 0.028 x $10^6$ $km^2$ (Davies *et al.*, 2012), which is 1.7% of the entire habitat (=area) beneath ice-shelves (Figs 2c & 4). Quantitative projections for the future are not available.

Hints for climate-induced changes in iceberg abundance and, thus, its impact are weak (Long *et al.,* 2002; Gutt *et al.,* 2011). Nevertheless areas potentially affected can roughly be quantified. If a 2 km maximum distance from icebergs <3 km long (Tournadre *et al.,* 2013) is taken, where they shape pelagic processes (Vernet *et al.*, 2011), the total area (iceberg area of 0.025 x $10^6$ $km^2$ plus 2 km ocean around) affected is 0.31 x $10^6$ $km^2$, which equals 1.1% of the entire SO. Using abundances and sizes of icebergs published by Orheim (1985) and an assumed average diameter in the largest size class of 5 km (measured values not available) this results in 0.5 x $10^6$ $km^2$. The entire area in which icebergs with a volume of >1 Gt per 1° (latitude) x 2° (longitude) occurred between 1992-2012 (Tournadre *et al.,* 2013) merged with the area of potential occurrence of icebergs >5 km observed 1999-2009 (Stuart & Long, 2011) is 20 x $10^6$ $km^2$, which is 70% of the SO. Most affected are areas off East Antarctica around 90° E, off-shore in the Ross and Weddell Seas, and the WAP area. Using the same data, 1.82 x $10^6$ $km^2$ are potentially affected by icebergs on the shelf, mainly in East Antarctica and WAP, which represents 61% of the entire shelf area.

*Dynamics of tidewater marine glaciers*

Between 1953 (on average) and 2001, most glaciers on the Antarctic Peninsula and South Georgia retreated (212 from 244 and 28 from 36 respectively) (Turner *et al.,* 2009b). If an average cliff length of 1 km is assumed and doubled to 2 km to include side-effects this results in a total of 480 km affected, which is 1.2% of the 39,200 km long Antarctic circumference (from Clarke & Johnston, 2003). If a distance of 2 km perpendicular to the cliff into the ocean, representing the area where calving happens plus side effects is assumed, this gives 1272 $km^2$, which is 0.04% of the <1000 m deep shelf, which occupies 2.97 x $10^6$ $km^2$ excluding ice-shelf covered areas (Clarke & Johnston, 2003; Fig. 4). For the remaining glaciers along the Antarctic Peninsula "…advances are generally small...", at South Georgia only two advanced (Turner *et al.*, 2009b) and for most of the other Antarctic glaciers climate change driven data are not available.

*Ozone depletion, increase in UV-B radiation*

The areas affected by the ozone hole and covered by < 80% sea-ice in November, the core-period for this approach, show a variation ranging from 3.92 x $10^6$ $km^2$ to 5.73 x $10^6$ $km^2$ for

9-15 November, 2009-2011. This amounts for 14 to 20% of the SO. In Fig. 4 the average for this period (three days merged) of 4.53 x $10^6$ $km^2$ is depicted. The area analysed for October of 5.82 x $10^6$ $km^2$ reached a maximum mainly due to the high temporal and spatial variation of a generally well-developed ozone hole including the WAP area not far off shore, as well as smaller areas where polynyas occur. The areas affected are mainly situated at the northern margin of the SO. As expected, with 1.14 x $10^6$ $km^2$ (4% of the SO) affected the areas are much smaller in December.

*Ocean Acidification*

According to the map provided by Orr *et al.* (2005), based on the IS92a "business-as-usual" scenario for future $CO_2$ emission, our calculations indicate that an area of 28.04 x $10^6$ $km^2$ could become under-saturated with respect to aragonite until the end of the 21st century, which is approximately 98% of the SO pelagic ecosystem, with the southern Ross Sea the only exception. Increase in $pCO_2$ is most obvious at intermediate water depths between approximately 100 and 700m in large off-shore areas (Hauck *et al.,* 2010, Kawaguchi *et al.,* 2013). Benthic systems are most affected in case of a tipping point from saturated to undersaturated conditions on most of the shelves, which represent 2.59% of the entire Antarctic sea-floor habitat and not so much in the naturally undersaturated deep-sea below the carbonate compensation depth.

*Areas multiply affected by environmental changes*

The entire area with one or more of the observed changes is 13.1 x $10^6$ $km^2$ in size, which amounts to 46 % of the SO (Figs 5a & 6). While areas affected by only one factor (from those analysed here) correspond to 33% of the SO surface, when superposing 2, 3, 4 and 5 factors the areas affected result in 11%, 2%, and <1% of the SO surface, respectively. Some areas north of the Sea-Ice Zone and closer to the continent especially in the Indian sector and in the

Amundsen Sea are affected but with a relatively low impact. The most intensively affected area is the Eastern Bellingshausen Sea (Fig. 6). Larger areas intermediately affected by 2 to 3 factors lay inshore and offshore in the Ross Sea area. Future changes are projected for almost the entire SO (Figs 5b & 6). This high coverage of 99% (28.4 x $10^6$ $km^2$) is due to the expected area-wide shift from aragonite over- to undersaturation. Large areas amounting to 36 and 43% of the SO will be affected by the impact of 2 and 3 factors combined, respectively. Much smaller areas representing 9 and 3% of the SO are projected to be affected by 4 and 5 factors. The highest impact in this sense occurs off shore in the Amundsen Sea, around the Peninsula and regionally on the shelf of East Antarctica including the Weddell Sea (Fig. 6).

## Discussion

### *Ocean warming*

More than 90% of anthropogenic greenhouse gas induced warming is absorbed by the world's ocean, slowing the atmospheric warming response to greenhouse gas forcing (Trenberth & Fasullo, 2013). Model studies suggest that the Southern Ocean (SO) dominates the global ocean heat uptake (Kuhlbrodt & Gregory, 2012). SO waters warmed over the past 50 years affecting the entire water column (Gille, 2002; Purkey & Johnson, 2010). A sea-surface warming above an assumed low physiological limit of 1K has so far only been reported for the WAP and in the adjacent eastern Bellingshausen Sea (Meredith & King, 2005; Schloss *et al*., 2012), which is a region of high diversity and significant ecosystem functioning, e.g. high productivity and growth of krill as an ecosystem service providing food for higher trophic levels represented by apex-predators, which occur globally (e.g., Ducklow *et al.,* 2006; Griffiths, 2010; Murphy *et al.,* 2012). For these reasons it represents an important site to compare with future projections to other regions of the SO where warming is expected. At 50 m water depth the area of critical warming shrinks to <10% of that at the surface (Meredith & King, 2005). Peck (2011) reviewed temperature tolerance of benthic invertebrates and extrapolated that most of the studied species could tolerate a warming in the range of 1-3 K. The last time the SO ecosystem experienced climate variations of this scale was during the transition from Mediaeval Warm Period (MWP; until 1287 AD) to the Little Ice Age (LIA; 1287-1850 AD) and its transition to modern warming (Bertler *et al*., 2011). The data from climate archives suggest that in the Ross Sea and adjacent areas in comparison to modern times (average from 1850 AD to today) SSTs during the MWP were warmer, and sea-ice extent as well as marine productivity were reduced. During the LIA, atmospheric temperatures were 2K cooler, with cooler SST, an increase in sea-ice and primary productivity. The reconstruction also suggests that rapid warming events occurred during the warmer periods (Bertler *et al.,* 2011). Support comes from studies, which suggest a large Ross

Sea latent heat polynya affected by upwelling of circumpolar deep water and an increase in primary productivity during the LIA (Leventer & Dunbar, 1988; Morales Maqueda *et al.,* 2004; Rhodes *et al.,* 2012).

It has been shown that the behaviours of ecologically relevant species respond more sensitively to warming than their measurable metabolism (Barnes & Peck, 2008). However, some species have not lost the capacity to compensate for chronic temperature increase of >3 K, e.g. the fish *Pagothenia borchgrevinki* (Seebacher *et al.,* 2005), which is consistent with hints that the recent temperatures are not the most elevated during the Holocene (Shevenell *et al.,* 2011). Cold-adapted benthic species can probably not survive in warmer deeper waters if they are endemic in cold shallow areas. Pelagic species can disperse easier than sessile benthic species into temperature stable areas and survive there. The growth of sponge populations mentioned in the IPCC AR4 (Anisimov *et al.,* 2007) and AR5 (Larsen *et al.,* 2014) only refers to exceptionally fast growing and recruiting species in an environment shaped by disturbances (Dayton, 1989; Gutt, 2001), also other sponge species can respond to environmental changes in both ways with exceptionally fast growth and mortality (Dayton *et al.,* 2013; Gutt *et al.,* 2013). Micro-evolution can contribute to species adaptation only if the capacity is sufficient to compensate for the relatively fast recent ocean warming (Peck *et al.,* 2009a). At the community rather than the species level in-shore habitats were found to be unique, valuable for higher trophic levels (Grange & Smith, 2013), rich in primary production and $CO_2$-uptake (Arrigo *et al.,* 2008, Quéguiner, 2013) and thus, further warming could result in an above-average loss in habitat diversity and ecosystems services (Grant *et al.*, 2013). Warming can also happen due to upwelling of Warm Deep Water offshore as a consequence of changing wind and current patterns and thus affect biological production processes (Dinniman *et al.,* 2012). A similar warming of the naturally relatively warm Upper Circumpolar Deep Water on the shelf of the WAP (Clarke *et al.,* 2009) could cause a range extension of species, e.g. of king crabs, since their temperature tolerance limit might exactly lay within the range of the T-increase from 1.04 to 1.47K in almost three decades (C.R. Smith *et al.*, 2012b; Griffiths *et al.,* 2013). Locally, a more severe impact could develop, when growing crab populations feed efficiently on hard shelled prey, to which the Antarctic benthic system is not well adapted. It can also not be excluded that non-investigated species have a similar tolerance limit, which lies exactly within a range of a warming of only a very few K. If such species are endemic for the SO they could extend their biogeographic ranges or non-indigenous species might invade the SO as 'aliens' (see Clarke *et al.,* 2005). Such a tipping point, beyond which some species die and others start to immigrate is known for a change from large diatoms to smaller cryophytes observed locally at air temperature of 0 K and reduced salinity (Moline *et al*., 2004). This could also explain the change from a krill to a salp-dominated pelagic (Atkinson *et al.,* 2008), or perhaps to a copepod dominated system. There has been substantial warming of the Southern Ocean concentrated in the Antarctic Circumpolar Current (Aoki *et al*., 2003, Böning *et al*., 2008, Gille 2002, 2008), where surface temperatures have increased by almost a degree but significant increases are recorded at all depths (Aoki *et al*., 2003, Gille 2008). In the east Antarctic region, 60° - 160°E, Robinson *et al.* (2014) found significant increases in zooplankton abundances since 1991 in all oceanographic zones between the sub-Antarctic and the Sea-Ice Zone based on Continuous Plankton Recorder data. There were shifts in dominance towards larger copepods, contrary to the hypothesis that warming will see a shift to smaller warm water species. Even if a warming in the deep Weddell Sea of <0.1K in 24 years as observed by Fahrbach *et al.* (2011) or a maximum of >2K increase to values above 0K predicted for the 2nd half of the 21st century by Hellmer *et al.* (2012) is too weak to affect organisms directly, the resulting changes in the oxygen ventilation of the SO, nutrients flux, or a possible collapse of ice-shelves could have an impact on entire marine communities. The impact at the sea surface and at 50m depth was partly considered moderate since the observed T-increase does not clearly exceed known tolerance limits of most investigated species but first signs of its effects on the plankton and benthic diatoms exist (Longhi *et al.,* 2003). Since species living at 50 m depth can survive in adjacent deeper, non-affected areas, this T-increase was also considered non-critical (Fig. 4). Since expected warming affects only regionally the ice-free relatively homogenous pelagic habitats it is assessed as moderate, but where it happens the effect is most likely severe.

*Shift of Polar Front*

The Southern Ocean fronts are -with exceptions- seen as one of the most effective barriers in the world's ocean (Clarke *et al.,* 2005; Knox, 2007; Thornhill *et al.*, 2008) especially for organisms inhabiting water depths < 500m due to the distinct temperature difference between water masses North and South of it (Sokolov & Rintoul, 2009b). A geographical shift of the Antarctic Circumpolar Current (ACC) fronts between 45° and 60°S by 60 km to the South and, consequently, a warming of 2 to 5.5 K in that area (Sokolov & Rintoul, 2009a) must result in a complete shift in the composition and functioning of the permanent open ocean habitat along the Polar frontal zone, characterised regionally by high primary production (Moore & Abbott, 2000) and diverse pelagic communities (Ward *et al.,* 2003, McLeod *et al.,* 2010, Hosie *et al.,* 2014). Due to these reason a modelling approach has projected high species turnover rates in this area (Cheung *et al.,* 2009). Southern Elephant seals *Mirounga leonina* along the Southern Ocean fronts seem to respond to changes in environmental conditions in their nutrition physiology and, as a consequence, in the feeding behaviour (Biuw *et al.,* 2007, Costa *et al.,* 2010, McIntyre *et al.,* 2011). Despite the lower limit of the frontal system of <500 m depth, processes and patchiness in the deeper plankton and deep-sea benthos can mirror changes in ecological processes in the euphotic zone (Pollard *et al.,* 2009; Sachs *et al.,* 2009; Veit-Köhler *et al.,* 2011). The discrete and high increase in SST related to a shift of the PF is the reason why this impact is considered as severe to the pelagic system.

An assumed buffering effect through carbon flux results in a supposed moderate impact to the deep-sea (Fig. 4).

*Sea-ice habitat*

In contrast to Arctic sea-ice trends, Antarctic sea-ice extent has increased over the recent past due to an increase in the Weddell and Ross Sea regions. The polynyas along the coastal regions around Antarctica are known as ice factories since they are sites of continuous ice production enhanced by strong katabatic winds. A change in wind patterns could cause a reduction in ice production and hence in ice extent. The predictions (e.g., CMIP5) indicate a decline in the Antarctic sea-ice extent in the last 3 decades but this is inconsistent with satellite observations. The latter have shown large declines of sea-ice in the Bellingshausen/Amundsen Seas, but these do not compensate for the increase in other areas (Bracegirdle *et al.,* 2008; Comiso, 2011). This inconsistency can be explained by tele-connections in the Atlantic (King, 2014). Decreases in ice extent may be caused by a warmer ocean that would shorten the length of the sea-ice season and keep the sea-ice cover from expanding as far north as usual and by changing wind patterns. A regional variability also becomes obvious when the period of sea-ice occurrence is split into the time before and after 1996 (Bintanja *et al.,* 2013). The forming and melting of sea-ice has a complex temporal pattern including climate-related changes driven by variations in circulation and temperature in both the atmosphere and ocean (Parkinson *et al.,* 2002; Stammerjohn *et al.,* 2008; Willmes *et al.,* 2009; Comiso *et al.,* 2011, Holland & Kwok, 2012). Also when the seasons are separately analysed, the areas with an increase are consistently larger than those with a decrease. An ice core based reconstruction of sea-ice variability over the past 130 years (Sinclair *et al.,* in press) suggests, that sea-ice extent in the Ross Sea region appears to be a relatively recent occurrence.

The changes so far already had an obvious impact on important pelagic ecosystem components, e.g., phytoplankton (Montes-Hugo *et al.,* 2009), Antarctic krill (Atkinson *et al.,* 2008), penguins (Lynch *et al.,* 2012), and seals (Simmonds & Isaak, 2007; Kovacs et al., 2012). Most of the biotic relationships are non-linear (Clarke & Harris, 2003), some are direct, some indirect (Trivelpiece *et al.,* 2011), and not all ecosystem functions become limited but benefit. Some species have a capacity to compensate the damage at least partly, e.g. whilst large krill populations at the northern margin of their occurrence shrink, more southerly situated populations undergo a slight increase (Atkinson *et al.,* 2008). Recent reviews suggest there have been cumulative impacts on sensitive pelagic and benthic ecosystems (Flores *et al.,* 2012; C.R. Smith *et al.*, 2012a) but also a certain resilience within the systems was assumed. On average all the IPCC scenarios show some decrease due to atmosphere and ocean warming (although very small in RCP2.6) in extent over the 21st century, see IPCC (2013, Figure 12.28). The future projections analysed here (Bracegirdle *et al.,* 2008) show a decrease especially in summer and autumn with a regional focus in the Amundsen-/Bellingshausen Seas and Indian sector of the SO, but not the spatial and temporal pattern as analysed for the past. At an assumed decrease of ice by 25%, a 10% increase in primary production is expected due increased photo-synthetically active radiation in an enlarged open water zone; not only the sea-ice extent but also the length of the sea-ice edge plays an important role, e.g. on krill (Arrigo & Thomas, 2004).

It can be expected that species with narrow ecological niches and adapted to conditions of the past glacial periods with much reduced primary production (Bonn *et al.,* 1998), suffer more from stress caused by an increase rather than from a decrease in food supply, but opportunistic species with broader tolerances might benefit. At least Dayton (1974) provided hints summarized by Gutt (2006) that a system with high phytoplankton production supports a more simple benthic system that that with a lower phytoplankton (food) supply. Latitudinal studies along a sea-ice gradient on the WAP suggest that macrofaunal species diversity may increase linearly with sea-ice loss on the shelf, while standing crop of macro- and megabenthos may exhibit abrupt changes (or tipping points) as annual sea-ice duration declines (C.R. Smith *et al.,* 2012a). Jones *et al.* (2014) predicted a global decrease by 2100 but increases in the SO in benthic biomass, which may result from climate-induced changes in the export flux from the euphotic layer to the specious deep-sea benthos (Brandt *et al.,* in press).

Species emigrated most likely during the shifts from glacial to interglacial periods and vice versa to areas with favourable conditions (Clarke & Crame, 1992; Clarke, 2003; Thadje *et al.,* 2008). They will potentially behave similarly, mobile species, and plankton faster than sessile benthic species, if the changes in the future occur slowly enough, and if refuges with favourable conditions persist in the southernmost marine areas. Gentoo penguins have already been observed to expand southward due to the loss of sea-ice (Lynch *et al.,* 2012), seals are known to have relocated their colonies during holocene temperature shifts (Hall *et al.,* 2006) and to respond to recent changes in ice dynamics in both directions, by an increase and decrease of populations size (Simmonds & Isaak, 2007; Bester, 2014). A specific trophic model with an assumed primary 8% species loss due to ice reduction results in a secondary 50% species loss and shows a high sensitivity of the sea-ice related habitat, which, is however less severe than in the Arctic (Mather *et al.,* 2012). The changes in the sea-ice in the past and future have been classified as intermediate (Fig. 4) since they already affected and will continue to affect not all but major ecosystem functions especially within the ice and pelagic habitats. Increases and decreases of season period and extent in the past have been considered equally because either ice-adapted or open-water preferring species will experience corresponding environmental stress.

### *Ice-shelf disintegration*

Autochthonous primary production cannot develop below ice-shelves due to the isolation from sunlight with the exception of chemoauthotroph communities (Domack *et al*., 2005a; Niemann *et al.,* 2009; Gutt *et al.,* 2011), thus, most of the life below the ice depends on advective food supply (Sañe *et al.,* 2011a). Benthic heterogeneity below the ice-shelves and close to the ice-shelf edge are shaped by the currents, which act as a food vector and are either flowing from the open water under the ice or vice versa (Barry & Dayton, 1988; Seiler & Gutt, 2007; Gutt *et al.,* 2011). In the latter case resulting oligotrophic conditions being in quality and quantity similar to the deep-sea change radically when the ice-shelves disintegrate (Bertolin & Schloss, 2009; Peck *et al.,* 2009b, Sañe *et al.,* 2011b) but also depend on the formation of polynyas (Cape *et al*., 2014). Calving of icebergs is a natural phenomenon that happens around the continent depending on the size and advance of the ice-shelves. It can be driven by natural climatological cycles or by the recent ocean and atmosphere warming at both sides of the Antarctic Peninsula. The large ice-shelves had so far been assumed to be stable (Hodgson *et al*., 2006) but a model experiment suggests that an extension of warm water below the Filchner-Ronne Ice Shelf during the 21th century could destabilize the floating ice masses (Hellmer *et al*., 2012). Since all organisms ranging from microbes to whales have been observed or are expected to be affected (Bertolin & Schloss, 2009; Raes *et al.,* 2010; Gutt *et al.,* 2011; Gutt *et al.,* 2013), including the regional extinction of specifically adapted deep-sea type species, ice-shelf disintegration can be assumed to be among the most severe changes - where it happens - that any marine system in the world could experience. The impact on the entire SO and global marine biodiversity would be severe if deep-sea organism types found in shallow depth turn out to be endemic for some of the isolated under ice-shelf habitats. The shift from an extremely oligotrophic to a normal Antarctic ecosystem must not necessarily be considered as a catastrophe as long as typical high-latitude communities establish in such areas and are not disturbed by further climate-change developments, e.g. land-run-off as a consequence from terrestrial deglaciation (Ashley & Smith, 2000). In addition to the benthic habitat below the ice-shelves, a specific fauna can exist at the subsurface of ice-shelves (Watanabe *et al.,* 2006; Rack, 2012), which can be endangered by further ice-shelf loss. Because the direct impact to the marine ecosystem is locally immense the overall impact was considered severe (Fig. 4).

*Scouring and drifting icebergs*

Calving of icebergs, their impact on the pelagic system and disturbance of benthic habitats are natural phenomena. Average disturbance rates are known to increase regional megabenthic diversity (Gutt & Piepenburg, 2003) and grounded as well as floating icebergs facilitate biological production in the upper 10 m of the pelagic system due to fertilisation and melting (Schwarz & Schodlok, 2009; Vernet *et al.,* 2011). Also, re-suspension of particles and nutrients in the nepheloid layer can be expected but have never been studied. Climate-driven changes in calving rates and the abundance of drifting icebergs (Bindschadler & Rignot, 2001; Long *et al.*, 2002) could lead to significant impacts on the marine ecosystem. However, direct observations do not exist.

Apparently icebergs occur on the shelf and off shore almost everywhere around the continent, with the exception of <1 Gt in 21 years per 1°x2° grid cell in some areas South of the PF off East Antarctic. 44% of the sea-floor area in the eastern Weddell Sea has been disturbed mainly at water depth <250 m by iceberg scouring over decades. This might be representative for the entire Antarctic shelf (Gutt & Starmans, 2001; Fig. 4). Most large icebergs studied by Stuart & Long (2011) remain in coastal waters, with a low abundance in the WAP area, and in the Bellingshausen and Amundsen Seas. Depending on which ice shelves are under future climate stress, changes in the disturbance regime of downstream-situated areas are to be expected (Smale & Barnes, 2008). This might especially happen east of the Antarctic

Peninsula, where icebergs drift far northward. Most serious changes can be expected if the Filchner-Ronne Ice Shelf was to disintegrate (Hellmer *et al.,* 2012).

If only areas of the sizes of icebergs and their surrounding are considered the impact to the ecosystem is relatively small compared to other climate-induced changes. However, the potentially affected habitats, benthic by grounding and pelagic by drifting icebergs, have similar high proportions of the corresponding habitats. Synergistic effects between grounded icebergs, melting of sea-ice and primary production (Arrigo *et al.*, 2002; Arrigo & van Dijken, 2003) and unexpected response at the sea-floor by sponges being key-species in the shallow water ecosystem (Dayton *et al.,* 2013) can not be quantified, but unpredictable tipping points seem to play an important role. On the one hand the shelf benthos is naturally shaped by iceberg groundings and, thus, no decrease in diversity and ecosystem functioning can be expected in case of moderate changes in disturbance, on the other hand the effects are long-lasting. As a consequence iceberg impact on the shelf is assessed as moderate (Fig. 4). The effect in open water is considered non-critical due to its ephemeral and local nature.

### *Tidewater marine glaciers*

The quantification of areas affected by tidewater glacier retreat results in comparably small areas. However, due to the proximity to the coast, grounding line or sea-floor, the disturbance by calving from glaciers to the sea-bed morphology, sediment composition and sea-bed inhabitants might locally be more intense than the impact due to ice-shelf disintegration. A high re-suspension of sediments leading to high local turbidity in the water column can be assumed where glaciers ground (Powell *et al.,* 1996; Dawber & Powell, 1997) especially in regions of high habitat complexity and assumed vulnerability (Grange & Smith, 2013). Also the impact of coastal glacier melting and their sediment load limit light availability for phytoplankton growth (Schloss *et al.,* 2014). Independently of the size of the areas affected this impact is considered to be severe (Fig. 4) because of it's affect on essential krill habitats and feeding whales (Nowacek *et al.,* 2011), and also because it happens in areas with significant seafloor habitat diversity (Grange & Smith, 2013).

*Ocean acidification*

The physico-chemical interactions shaping the carbonate system in the oceans are nonlinear (Trela *et al.,* 1995), have a considerable temporal and spatial variation (Hauck *et al.,* 2010) and interact with other global changes such as increased irradiance and warming (Gao *et al*., 2012; Li *et al.,* 2012; Torstensson *et al.,* 2013). If current projections are correct 98% of the SO will be undersaturated with respect to aragonite by 2100 AD (Orr *et al.*, 2005). Under the IPCC IS92a scenario, SO wintertime aragonite undersaturation is projected to occur already no later than 2038 (McNeil & Matear, 2008). Additional energetic costs for organisms resulting from the need to build skeletal mass in an ocean with a low aragonite saturation state have to be considered (Watson *et al.,* 2012). Shell dissolution might also lower resistance to predation pressure on shell forming organisms (Gazeau *et al.,* 2013). Key species in the world's ocean pelagic and benthic systems, such as the calcifying coccolithophorids and pteropods, echinoderms and corals are severely affected (Doney *et al.,* 2009; Riebesell & Tortell, 2011; Bednaršek *et al.,* 2012; Wittmann & Pörtner, 2013) and, thus, important trophic interrelationships could change. Also a change in the efficiency of phyotosynthesis and the biological carbon pump must be expected (Riebesell *et al.,* 2007; Tortell *et al.,* 2009; Hofmann *et al.,* 2011). A large-scale and long-term projection for the SO shows that within a century important krill recruitment habitats could be seriously affected (Kawaguchi *et al.,* 2013). Some calcifying plankton will even experience detrimental carbonate conditions earlier than previously thought (McNeil & Matear, 2008; McClintock *et al.,* 2009; Bednaršek *et al.*, 2012; Mattsdotter Bjork *et al.,* 2014). Foraminiferan shell weight has been found to be reduced by 30-35% at the northern margin of the modern SO compared to pre-industrial weights linked to atmospheric CO2 and ocean pH (Moy *et al.,* 2009). However, some projections point towards a 30 y delay in acidification in the Ross Sea due to sea-ice cover and deep-water entrainment (McNeil *et al.,* 2010), which could allow organisms to adapt eventually through microevolution (Collins *et al.,* 2014) as observed for some species at the global level by Wittman & Pörtner (2013). Indeed, Cummings *et al.* (2011) showed that in the Antarctic bivalve *Laternula elliptica* gene expression might change in response to acidification. Due to the lack of comprehensive data on Antarctic pelagic ecosystems response to acidification this impact is assessed as intermediate. The impact to the benthic systems is also considered intermediate because only the shelves are expected to experience significant changes but these are rich in biomass and are assumed to contribute essentially to ecosystem services especially to remineralisation (Fig. 4).

Another effect might come from the depletion of seawater borate ions ($B(OH)^{4-}$) under increasing absorption of $CO_2$ (Brewer & Hester, 2009). Borates absorb sound at low-frequency. Under doubling $CO_2$ ocean concentrations sound at frequencies that are important for marine mammals will travel some 70% farther with assumed but unknown impact to these animals.

*Increased UV-B impact due to ozone depletion*

In our results, the temporal spatial variation of areas exposed to increased UV-B was principally due to the highly dynamic stratospheric ozone hole rather than to variations in sea-ice distribution. As a consequence of the approach to exclude areas where the water column is shielded from UV-B by < 80% sea-ice cover but to include the spatial variation of the ozone hole, the area affected is quite large compared to the other impacts. The analysis considering data from October, November with three replicates, and December shows that the most critical phase starts when elevated UV-B penetrates into the SO due to the melting of sea-ice, but when the ozone hole is still present before it fills in December. A slowly long-term recovering ozone hole is foreseen (Perlwitz *et al.,* 2008), with full recovery maybe achieved by the end of the 21st century (Turner *et al.,* 2013a). Although large marine areas that are affected by the ozone hole are still covered by sea-ice (Lister *et al.*, 2010), in areas of decreasing sea-ice, this might no longer be the case (Moreau *et al.,* in press). Arrigo *et al.* (2003) estimated a loss of only <0.25% on primary production between August and December due to UV-B, but in areas such as the WAP an increase in production related to decreased sea-ice (and therefore, probably more exposure to UV-B) has been evident (Ducklow *et al.,* 2013). While many studies have shown that UV-B negatively affects aquatic organisms, effects on ecosystems remain uncertain (Häder *et al.,* 2007). Mesocosm studies on subantarctic plankton suggest that UV-B has more an effect on plankton composition than on overall biomass (Roy *et al.,* 2006), therefore being an important factor in ecosystem function. In the natural environment, however, the effects could be attenuated by vertical mixing of the water column (Ferreyra *et al.,* 2006), the presence of coloured dissolved organic matter as well as the presence of sea-ice (Arrigo *et al.,* 2003), and the synthesis of photoprotective compounds (Helbling *et al.,* 1996; Hernando *et al.,* 2002). When the ice breaks up and a maximum of transparency allows the radiation to penetrate deeply into the clear water, shallow habitats might be severely affected, as is the case for macroalgae and their consumers (Zacher *et al.*, 2007). A variety of other organisms at different life stages, including fish (Karentz & Bosch, 2001; Huovinen & Gómez, 2013) might also be indirectly affected through the food web. Endotherms are everywhere exposed to the increased UV-B radiation where the ozone hole exists when they stay on land or on the ice and might suffer from eye damage (Hemmigsen & Douglas, 1970). With regards to the effects of UV-B on the biomass of key organisms like krill, results are contradictory (Bidigare, 1989; IPPC, 2013), depending also on the yearly variation in the extent of the ozone hole (Mangel *et al.*, 2010). Overall, since UV-B increase happens only for a limited period of the year and has a considerable interannual and short-term variability with the consequence that large areas are not permanently exposed the effect is assumed to be moderate (Fig. 4). Despite weak hints that the ozone hole will slowly close in the next decades not projections are available.

*Areas multiply affected by environmental changes in a wider context*

Areas expected to show environmental changes, assumed to cause potential stress to organisms and impact marine communities, are larger than areas that have already experienced such changes and effects. This is mainly due to a combination of two factors, the shift from aragonite over- to undersaturation in almost the entire SO within the next decades and large areas expected to experience a decrease in sea-ice cover summed-up for all four seasons, in contrast to ocean acidification (Orr *et al.,* 2005) a scenario being specific for both polar regions (for the Arctic see Comiso *et al.,* 2008). The latter is against the still ongoing trend of total sea-ice increase in the SO. Combined impact factors are obvious especially on the shelves since in iceberg disturbance and acidification both, the sea-floor and pelagic habitats are expected to be disturbed or significantly be affected. The areas around and adjacent to the Antarctic Peninsula will remain a hot-spot in changes with respect to superimposed effects but less obvious than in the past due to larger circumpolar inshore and offshore areas expected to get under climate stress.

Our results offer tools to identify knowledge gaps to help design future studies on climate change impact in the SO ecosystem. In terms of size of areas affected, sea-ice and acidification require substantial attention and efforts to better constrain their effects. Because of their severe impact ice-shelf disintegration and resulting iceberg scouring could also become a focus of future approaches, as well as the added effects of regional warming in unique coastal systems and at the northern margin of the SO. Here we have identified several factors that simultaneously affect a certain area. One of the biggest challenges in this context is to consider their synergic effects on single species and communities (Clarke & Harris, 2003). Our spatially explicit area-based concept is a first assessment of the severity of environmental-change impact. However, the magnitude of threads for the loss of habitats is not just a function of the area affected but also of habitat turn-over and physical-biological interactions. The scientific basis especially of conservation ecology must consider biodiversity and productivity hotspots (Myers *et al.,* 2000), their heterogeneity, patterns and locations as well as the spatial overlap with areas of single and multiple factors of environmental change.

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## Figure legends

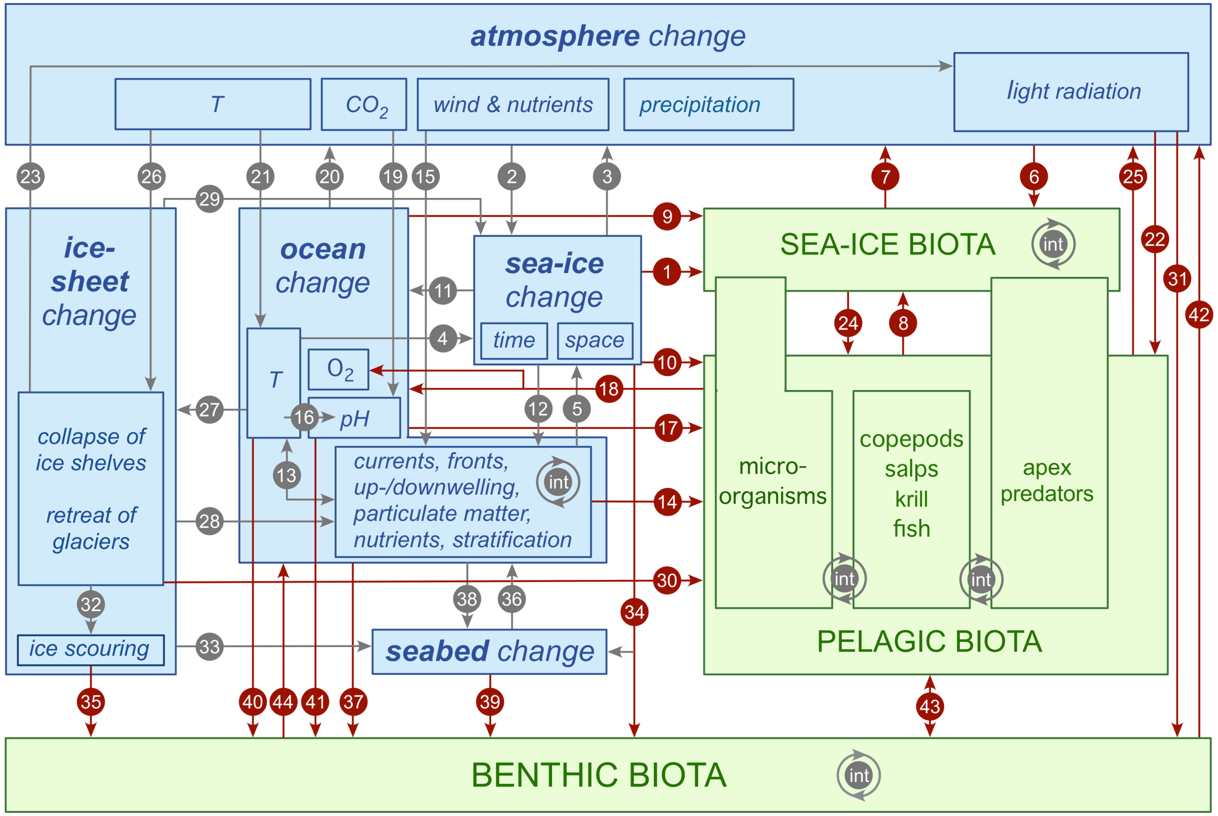
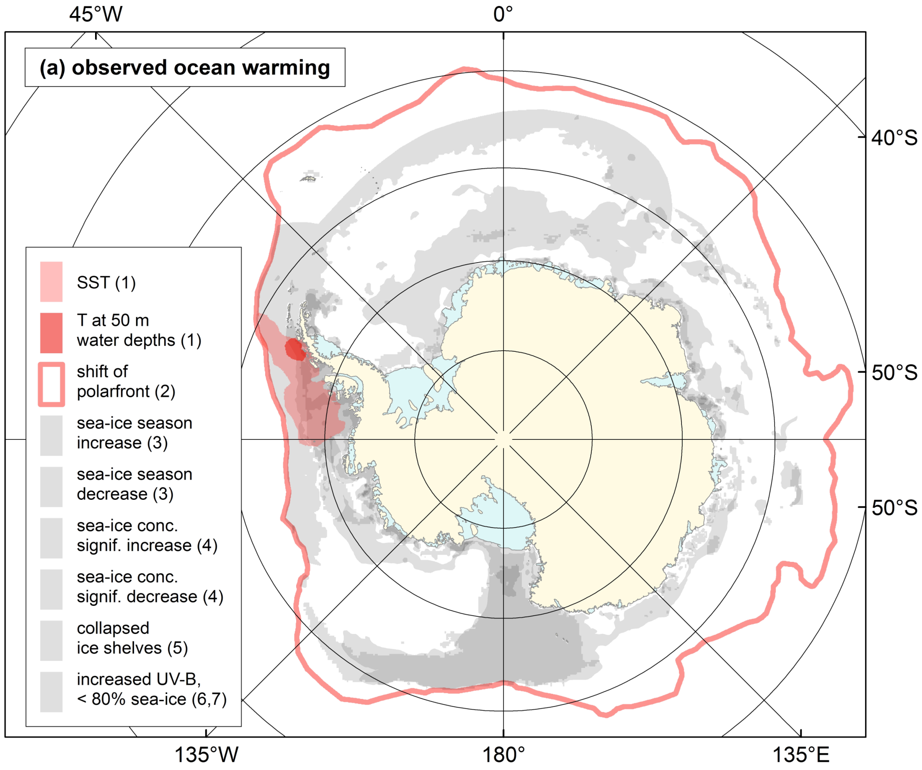
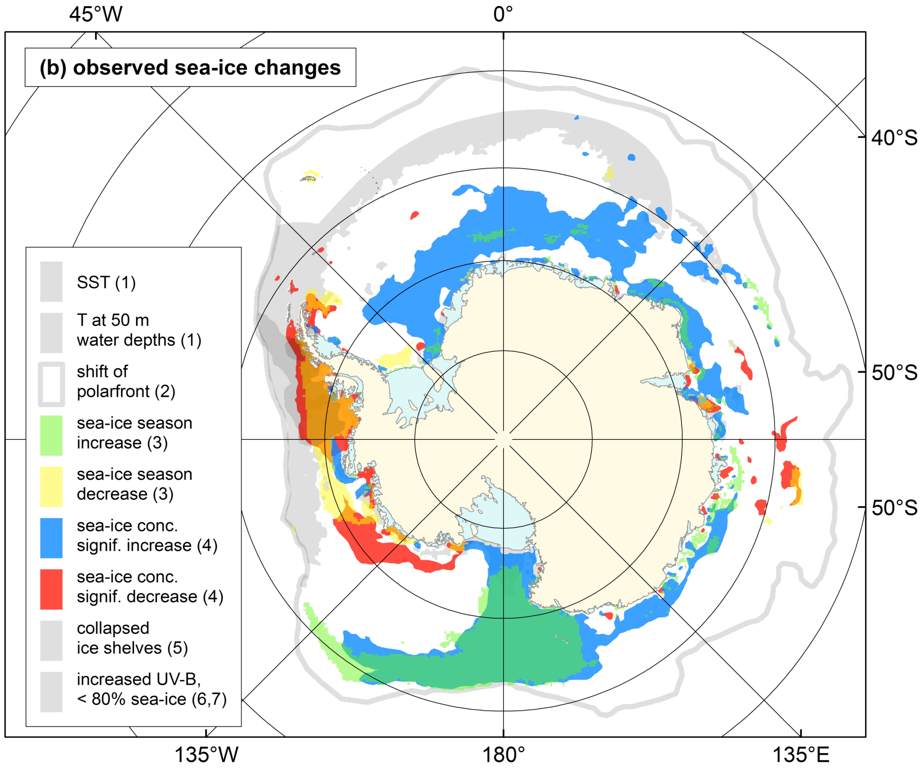
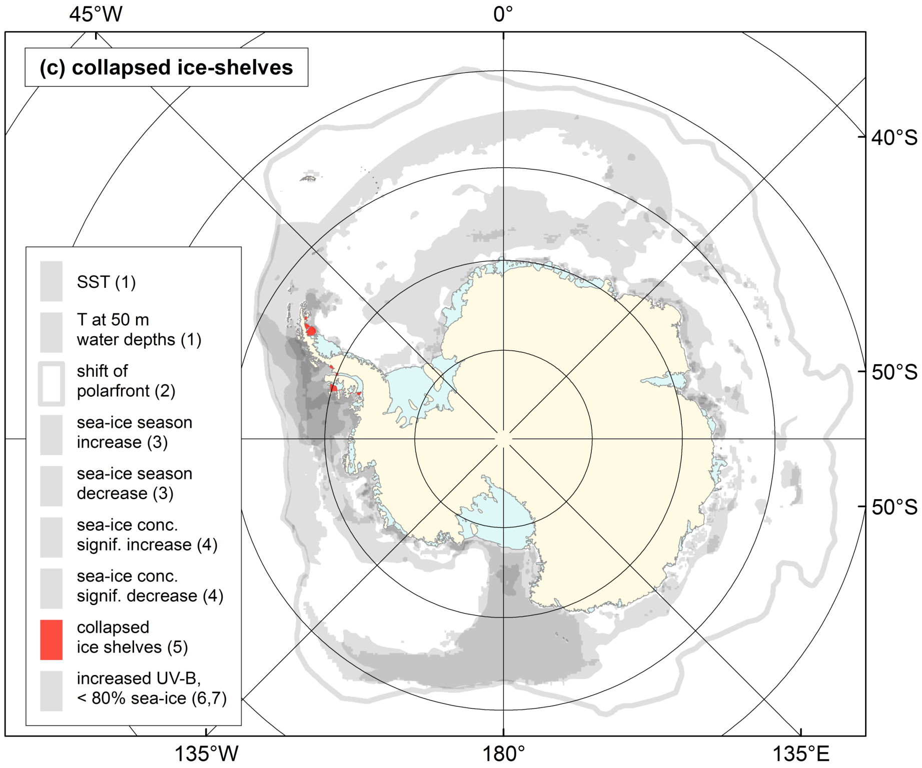


Fig. 1: Relationships between changes in the living and non-living nature of the SO, depicted in a condensed and simplified way. For description of individual links see S1. Arrows indicate directed impact. Interactions between biota and the environment are depicted in red. Links within


45°W
0°
(a) observed ocean warming
40°S
50°S
50°S
135°W
180°
135°E
SST (1)
T at 50 m water depths (1)
shift of polarfront (2)
sea-ice season increase (3)
sea-ice season decrease (3)
sea-ice conc. signif. increase (4)
sea-ice conc. signif. decrease (4)
collapsed ice shelves (5)
increased UV-B, < 80% sea-ice (6,7)


45°W
0°
(b) observed sea-ice changes
40°S
50°S
50°S
SST (1)
T at 50 m water depths (1)
shift of polarfront (2)
sea-ice season increase (3)
sea-ice season decrease (3)
sea-ice conc. signif. increase (4)
sea-ice conc. signif. decrease (4)
collapsed ice shelves (5)
increased UV-B, < 80% sea-ice (6,7)
135°W
180°
135°E


45°W
0°
(c) collapsed ice-shelves
40°S
50°S
50°S
SST (1)
T at 50 m water depths (1)
shift of polarfront (2)
sea-ice season increase (3)
sea-ice season decrease (3)
sea-ice conc. signif. increase (4)
sea-ice conc. signif. decrease (4)
collapsed ice shelves (5)
increased UV-B, < 80% sea-ice (6,7)
135°W
180°
135°E

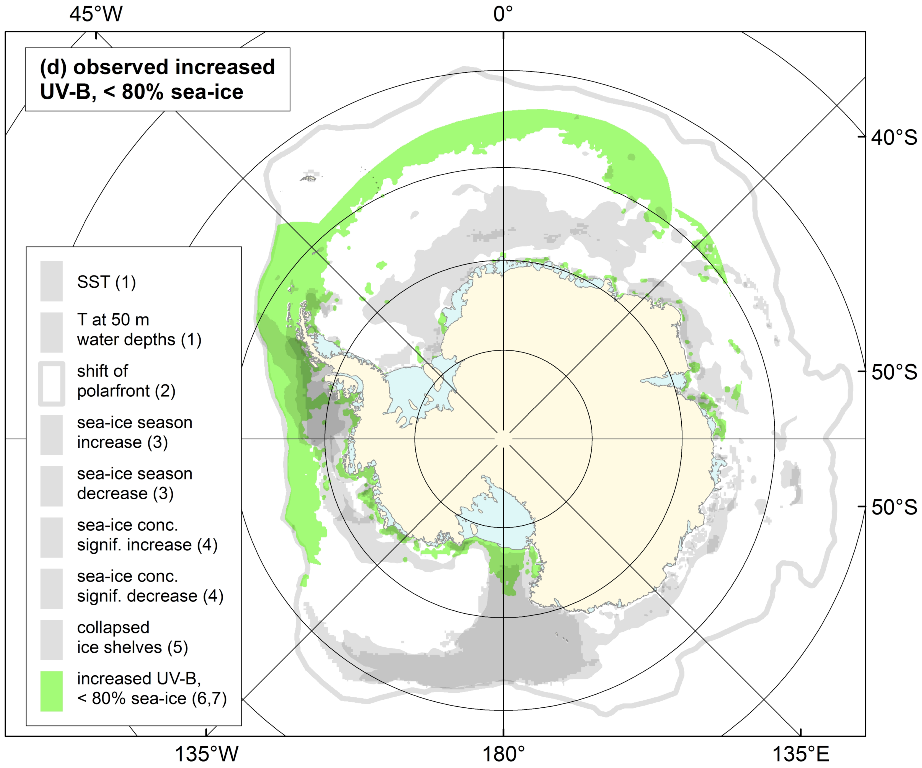
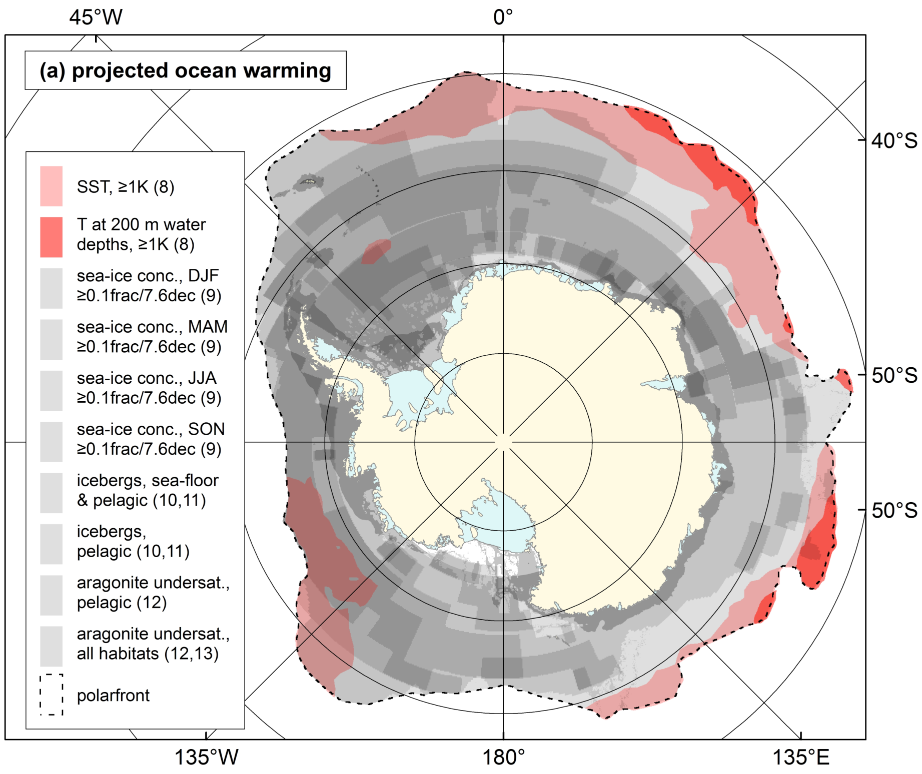
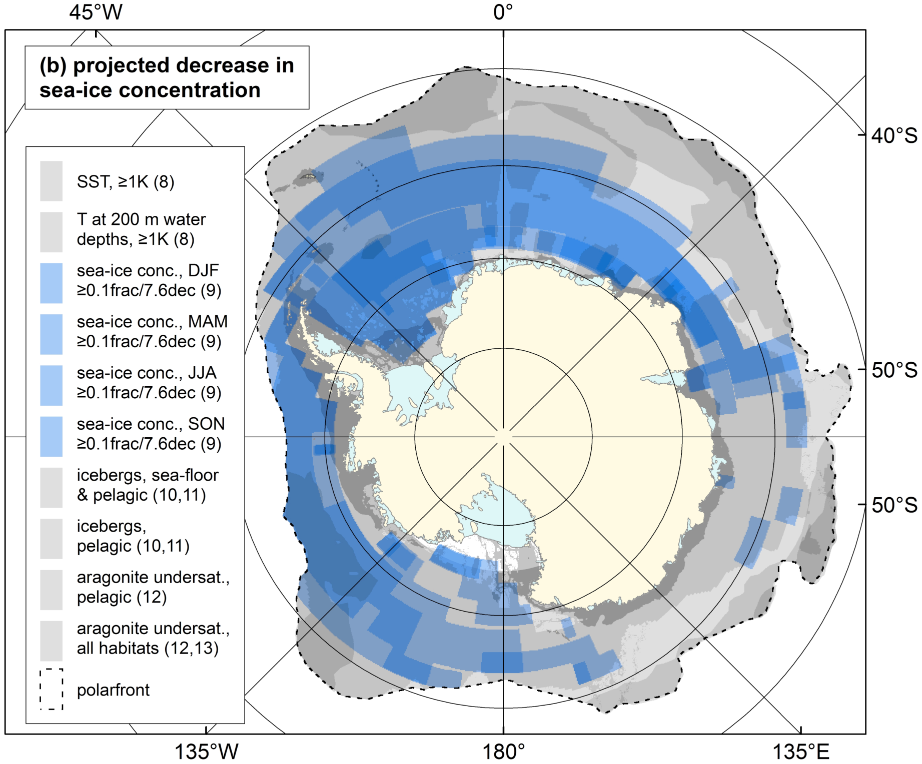
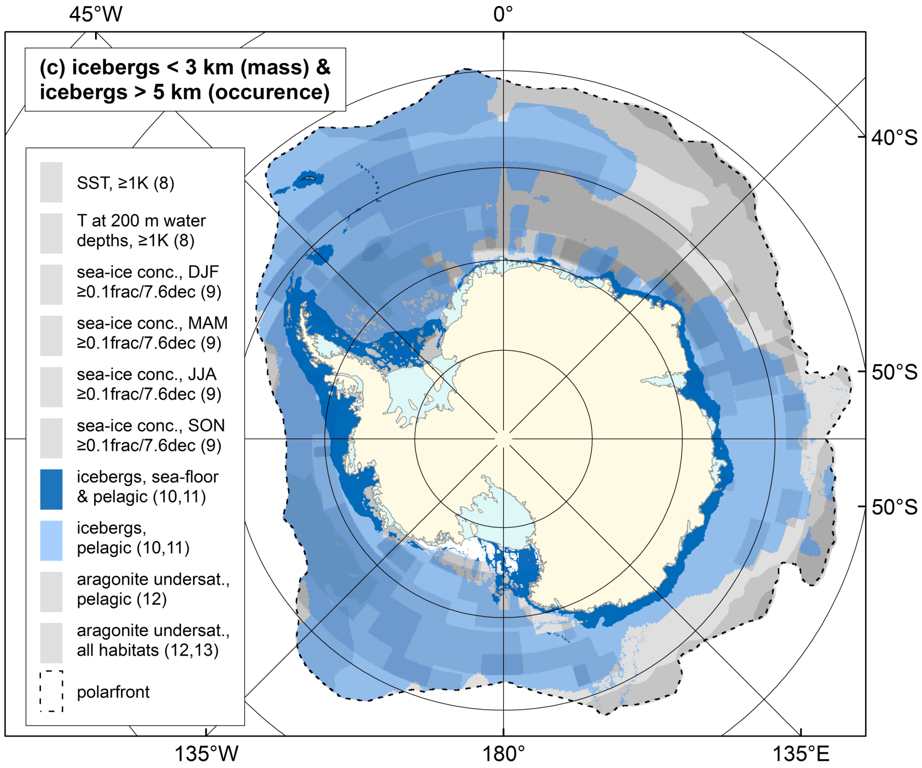


Fig. 2: Areas within the SO affected by observed climate change phenomena (in the past); for references comprising sources of information (coded in parentheses) see Table 1. a) Ocean warming, b) sea-ice changes, c) collapsed iceshelves, d) increased UV-B due to ozone depletion in open water (< 80% sea-ice cover). Specific changes are highlighted by colour; all others for comparison reasons depicted in grey. Polar stereographic projection.


45°W
0°
(a) projected ocean warming
40°S
50°S
50°S
135°W
180°
135°E
SST, ≥1K (8)
T at 200 m water depths, ≥1K (8)
sea-ice conc., DJF ≥0.1frac/7.6dec (9)
sea-ice conc., MAM ≥0.1frac/7.6dec (9)
sea-ice conc., JJA ≥0.1frac/7.6dec (9)
sea-ice conc., SON ≥0.1frac/7.6dec (9)
icebergs, sea-floor & pelagic (10,11)
icebergs, pelagic (10,11)
aragonite undersat., pelagic (12)
aragonite undersat., all habitats (12,13)
polarfront


(b) projected decrease in sea-ice concentration
45°W
0°
40°S
50°S
50°S
135°W
180°
135°E
SST, ≥1K (8)
T at 200 m water depths, ≥1K (8)
sea-ice conc., DJF ≥0.1frac/7.6dec (9)
sea-ice conc., MAM ≥0.1frac/7.6dec (9)
sea-ice conc., JJA ≥0.1frac/7.6dec (9)
sea-ice conc., SON ≥0.1frac/7.6dec (9)
icebergs, sea-floor & pelagic (10,11)
icebergs, pelagic (10,11)
aragonite undersat., pelagic (12)
aragonite undersat., all habitats (12,13)
polarfront


(c) icebergs < 3 km (mass) & icebergs > 5 km (occurence)
SST, ≥1K (8)
T at 200 m water depths, ≥1K (8)
sea-ice conc., DJF ≥0.1frac/7.6dec (9)
sea-ice conc., MAM ≥0.1frac/7.6dec (9)
sea-ice conc., JJA ≥0.1frac/7.6dec (9)
sea-ice conc., SON ≥0.1frac/7.6dec (9)
icebergs, sea-floor & pelagic (10,11)
icebergs, pelagic (10,11)
aragonite undersat., pelagic (12)
aragonite undersat., all habitats (12,13)
polarfront
45°W
0°
40°S
50°S
50°S
135°W
180°
135°E

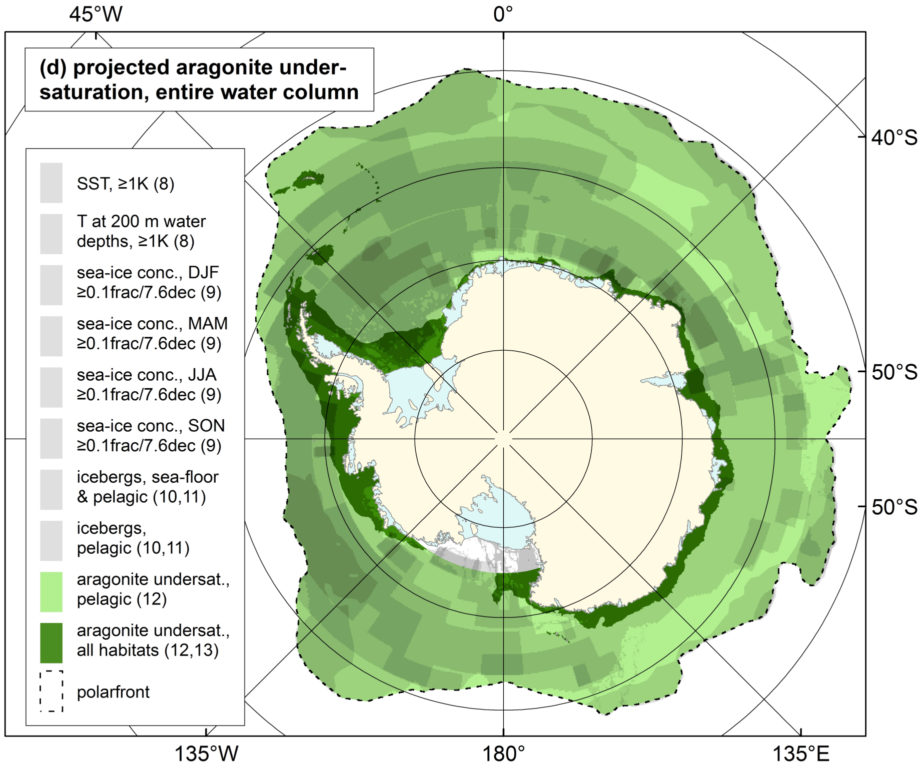


Fig. 3: Areas within the SO affected in the future by projected climate change phenomena (for the future) including iceberg occurrences; for references comprising sources of information (coded in parentheses) see Table 1. a) Ocean warming, b) decrease in sea-ice concentration, c) iceberg occurrences, d) aragonite undersaturation ("all habitats" refers to the impact to both habitats, pelagic and sea-floor. Specific changes are highlighted by colour, all others for comparison reasons depicted in grey. Polar stereographic projection.

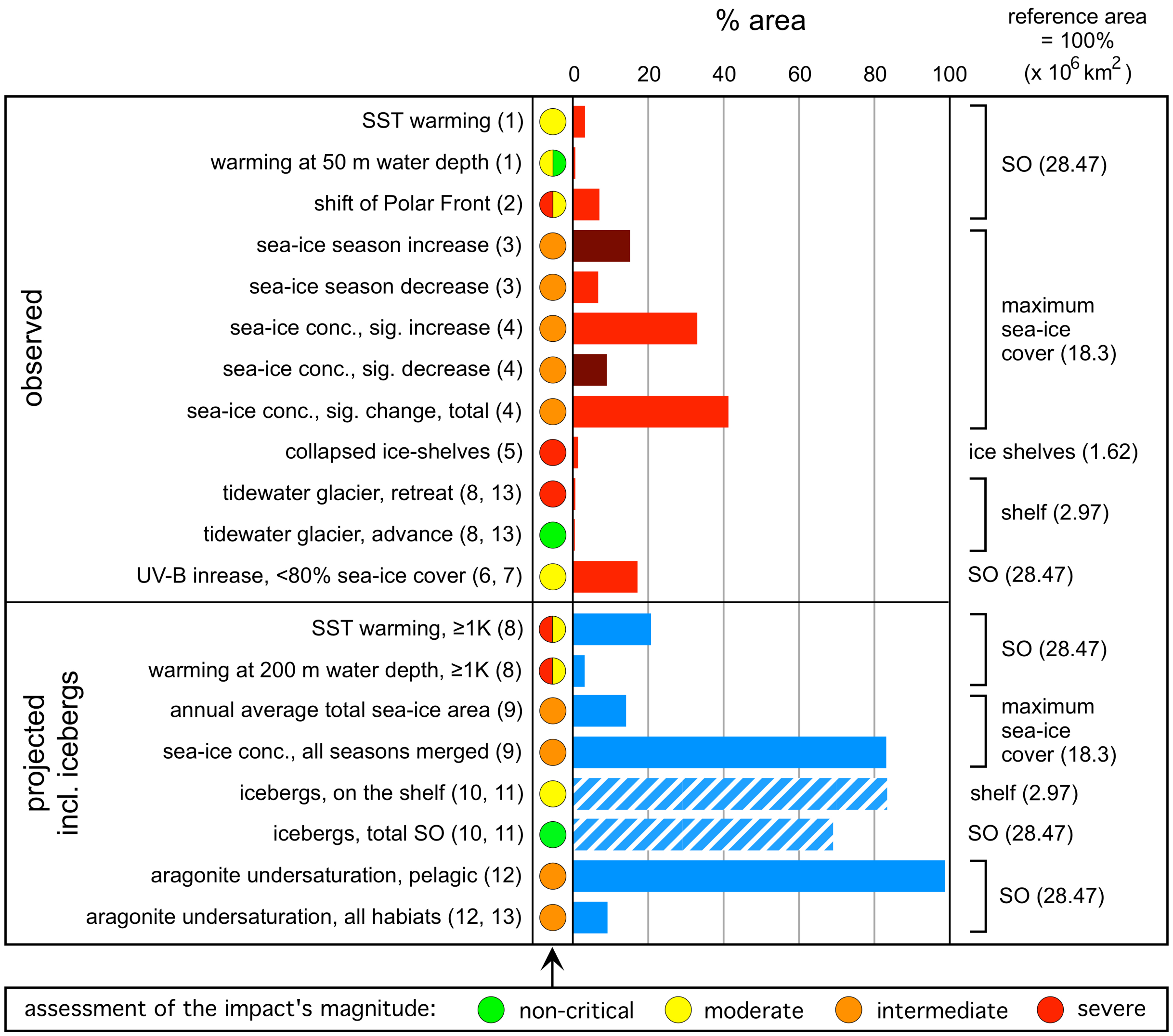
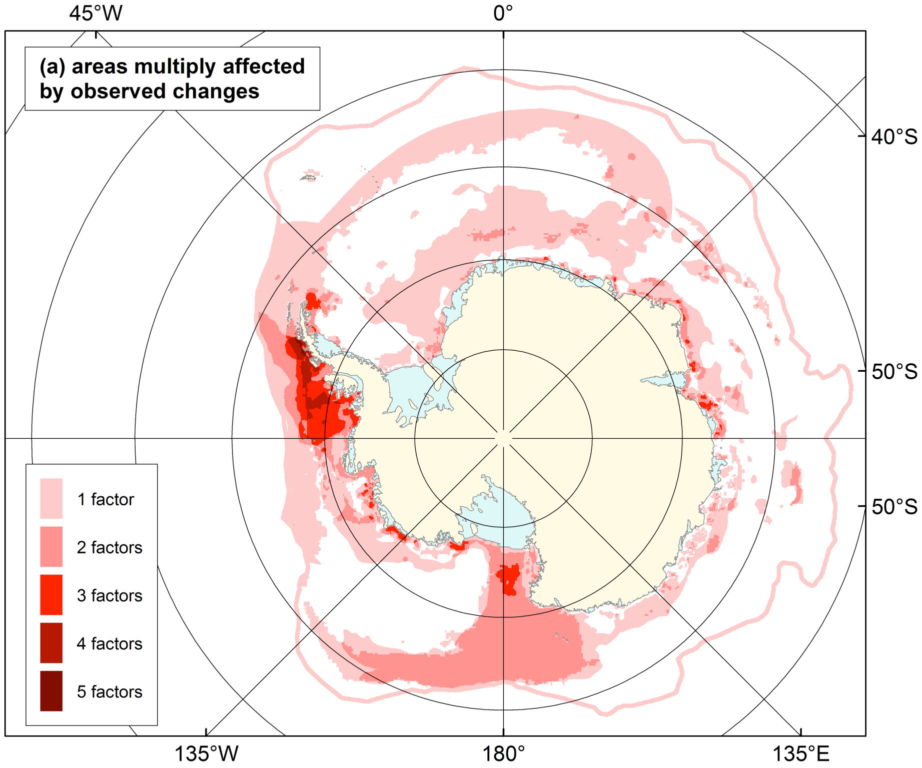

% area
reference area = 100% (x 10^6 km^2)
0
20
40
60
80
100
observed
SST warming (1)
warming at 50 m water depth (1)
shift of Polar Front (2)
sea-ice season increase (3)
sea-ice season decrease (3)
sea-ice conc., sig. increase (4)
sea-ice conc., sig. decrease (4)
sea-ice conc., sig. change, total (4)
collapsed ice-shelves (5)
tidewater glacier, retreat (8, 13)
tidewater glacier, advance (8, 13)
UV-B inrease, <80% sea-ice cover (6, 7)
projected incl. icebergs
SST warming, ≥1K (8)
warming at 200 m water depth, ≥1K (8)
annual average total sea-ice area (9)
sea-ice conc., all seasons merged (9)
icebergs, on the shelf (10, 11)
icebergs, total SO (10, 11)
aragonite undersaturation, pelagic (12)
aragonite undersaturation, all habiats (12, 13)
SO (28.47)
maximum sea-ice cover (18.3)
ice shelves (1.62)
shelf (2.97)
SO (28.47)
SO (28.47)
maximum sea-ice cover (18.3)
shelf (2.97)
SO (28.47)
SO (28.47)
assessment of the impact's magnitude:
non-critical
moderate
intermediate
severe

Fig. 4: Quantification of areas affected by observed (past) and projected (future) changes in the SO and qualitative assessment of the impact's magnitude. Observed changes in red, to more polar conditions in dark red; projected changes in blue, potentially affected areas by icebergs in hatched blue. For references comprising sources of information (coded in parentheses) see Table 1.



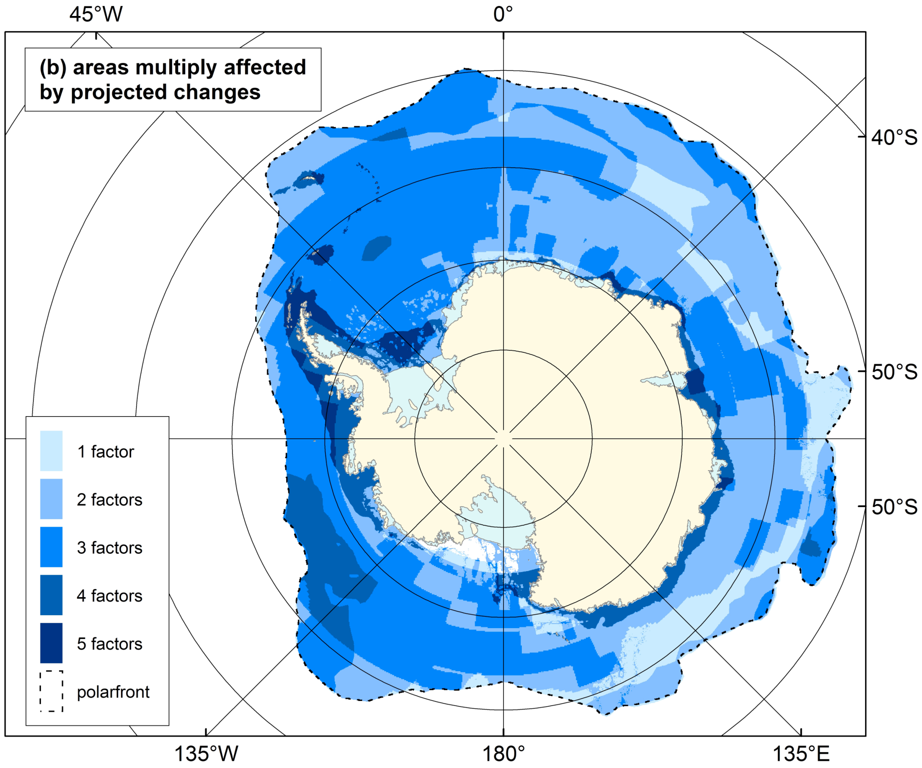


Fig. 5: Areas multiply affected by environmental changes. a) Observed (past) changes, b) projected (future) changes. Polar stereographic projection.

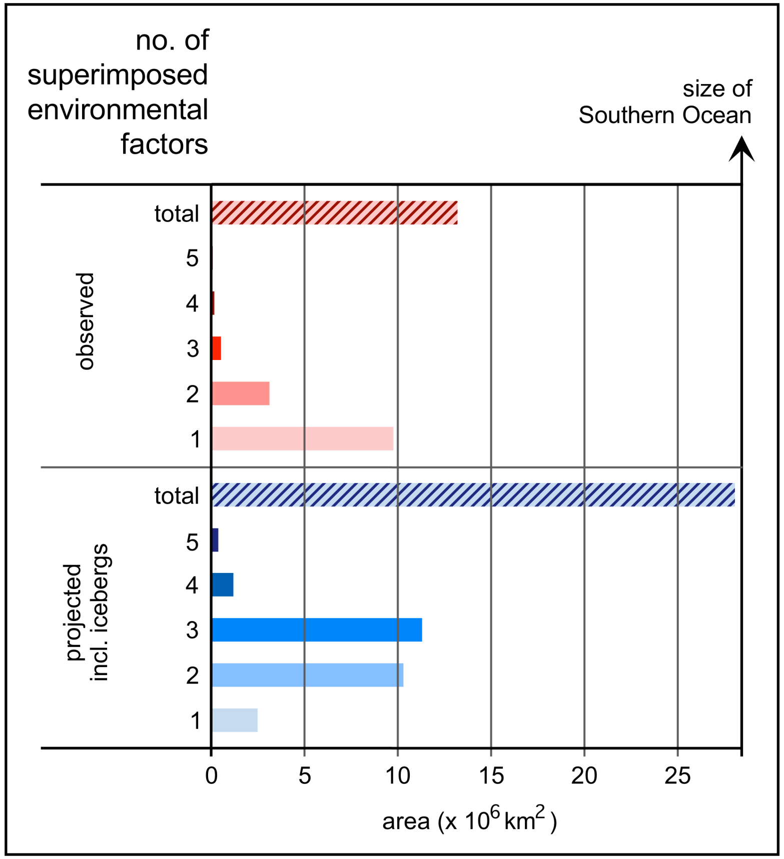


Fig. 6: Quantification of multiply affected areas by observed (past: red) and projected (future including icebergs: blue) environmental changes.

Table 1: Absolute and relative sizes of areas affected by various climate change phenomena.
Results with a source code for references are also shown in Fig. 2, 3 and/or Fig. 4.

| parameter | source | source code** | Fig. | Δ area ($10^6$ km$^2$) | Δ area (%) | 100% ($10^6$ km$^2$) |
|---|---|---|---|---|---|---|
| OBSERVED | | | 2 | | | |
| SST warming, 1955-1998 | Meredith & King, 2005 | 1 | 2a | 0.73 | 2.6 | 28.47 [a] |
| warming at 50m depth, 1955-1998 | Meredith & King, 2005 | 1 | 2a | 0.05 | 0.2 | 28.47 [a] |
| shift of Polar Front, 1992-2007 | Sokolov & Rintoul, 2009b | 2 | 2a | 1.93 | 6.8 | 28.47 [a] |
| sea-ice season, 1979-1999, increase | Parkinson, 2002 | 3 | 2b | 2.68 | 14.7 | 18.3 [b] |
| sea-ice season, 1979-1999, decrease | Parkinson, 2002 | 3 | 2b | 1.15 | 6.3 | 18.3 [b] |
| sea-ice conc., winter (JJA), 1979-2012, sig. increase | Comiso, 2000 | | | 0.88 | 4.8 | 18.3 [b] |
| sea-ice conc., winter (JJA), 1979-2012, sig. decrease | Comiso, 2000 | | | 0.08 | 0.4 | 18.3 [b] |
| sea-ice conc., spring (SON), 1979-2012, sig. increase | Comiso, 2000 | | | 1.08 | 5.9 | 18.3 [b] |
| sea-ice conc., spring (SON), 1979-2012, sig. decrease | Comiso, 2000 | | | 0.06 | 0.3 | 18.3 [b] |
| sea-ice conc., summer (DJF), 1979-2012, sig. increase | Comiso, 2000 | | | 0.76 | 4.2 | 18.3 [b] |
| sea-ice conc., summer (DJF), 1979-2012, sig. decrease | Comiso, 2000 | | | 0.58 | 3.2 | 18.3 [b] |
| sea-ice conc., autumn (MAM), 1979-2012, sig. increase | Comiso, 2000 | | | 0.42 | 2.3 | 18.3 [c] |
| sea-ice conc., autumn (MAM), 1979-2012, sig. decrease | Comiso, 2000 | | | 0.35 | 1.9 | 18.3 [b] |
| sea-ice conc., annual mean, 1979-2012, sig. increase | Comiso, 2000 | | | 5.18 | 28.3 | 18.3 [b] |
| sea-ice conc., annual mean, 1979-2012, sig. decrease | Comiso, 2000 | | | 0.94 | 5.1 | 18.3 [b] |
| sea-ice conc., annual mean, 1979-2012, sig. in- & decrease | Comiso, 2000 | | | | | 18.3 [b] |
| sea-ice conc., seasons merged, 1979-2012, sig. increase | Comiso, 2000 | 4 | 2b | 6.06 | 33.1 | 18.3 [b] |
| sea-ice conc., seasons merged, 1979-2012, sig. decrease | Comiso, 2000 | 4 | 2b | 1.55 | 8.5 | 18.3 [b] |
| sea-ice conc., seasons merged, 1979-2012, sig. in- & decrease | Comiso, 2000 | 4 | 2b | 7.61 | 41.6 | 18.3 [b] |
| collapsed ice-shelves, since 1960s | Davies *et al.,* 2012 | | | 0.028 | 1.7 | 1.62 [c] |
| | Barnes & Peck, 2008 | 5 | 2c | | | |
| UV-B increase, <80% sea-ice cover, 10-12 Oct 2009-2011 | exp-studies.tor.ec.gc.ca/cgi-bin/selectMap & icdc.zmaw.de/seaiceconcentration_asi_ssmi.html | | | 5.82 | 20.4 | 28.47 [a] |
| UV-B increase, <80% sea-ice cover, 7-9 Nov 2009-1011 | | 6, 7 | 2d | 3.92 | 13.8 | 28.47 [a] |
| UV-B increase, <80% sea-ice cover, 10-12 Nov 2009-2011 | | 6, 7 | 2d | 4.53 | 15.9 | 28.47 [a] |
| UV-B increase, <80% sea-ice cover, 13-15 Nov 2009-2011 | | 6, 7 | 2d | 5.73 | 20.1 | 28.47 [a] |

| | | | | | | |
|---|---|---|---|---|---|---|
| UV-B increase, <80% sea-ice cover, 10-12 Dec 2009-2011 | | | | 1.14 | 4.0 | 28.47[a] |
| tidewater glacier, retreat | Turner *et al.,* 2009b; Cook *et al.,* 2005 | 8, 13 | | 0.00127 | 0.004 | 2.97[e] |
| tidewater marine glacier, advance | Turner *et al.,* 2009b; Cook *et al.,* 2005 | 8, 13 | | ≥ 0 | 4<br>≥ 0 | 2.97[e] |
| PROJECTED (incl. iceberg occurrences*) | | | 3 | | | |
| SST warming, 2000-2100, summer, ≥1K | Turner *et al.,* 2009b | | | 3.26 | 11.5 | 28.47[a] |
| SST warming, 2000-2100, winter, ≥1K | Turner *et al.,* 2009b | | | 4.35 | 15.9 | 28.47[a] |
| SST warming, 2000-2100, all year, ≥1K | Turner *et al.,* 2009b | 8 | 3b | 5.87 | 20.6 | 28.47[a] |
| warming at 200m depth, 2000-2100, summer, ≥1K | Turner *et al.,* 2009b | | | 0.50 | 1.8 | 28.47[a] |
| warming at 200m depth, 2000-2100, winter, ≥1K | Turner *et al.,* 2009b | | | 0.64 | 2.3 | 28.47[a] |
| warming at 200m depth, 2000-2100, all year, ≥1K | Turner *et al.,* 2009b | 8 | 3b | 0.78 | 2.7 | 28.47[a] |
| sea-ice conc., summer (DJF), ≥0.1 frac/7.6dec | Bracegirdle *et al.,* 2008 | 9 | 3b | 2.43 | 13.3 | 18.3[b] |
| sea-ice conc., autumn (MAM), ≥0.1 frac/7.6dec | Bracegirdle *et al.,* 2008 | 9 | 3b | 3.99 | 21.8 | 18.3[b] |
| sea-ice conc., winter (JJA), ≥ 0.1frac/7.6dec | Bracegirdle *et al.,* 2008 | 9 | 3b | 10.34 | 56.5 | 18.3[b] |
| sea-ice conc., spring (SON), ≥ 0.1frac/7.6dec | Bracegirdle *et al.,* 2008 | 9 | 3b | 8.86 | 48.4 | 18.3[b] |
| sea-ice conc., all seasons merged, ≥0.1 frac/7.6dec | Bracegirdle *et al.,* 2008 | 9 | 3b | 15.14 | 82.7 | 18.3[b] |
| annual average total sea-ice area, 2004/23 - 2080/99 | Bracegirdle *et al*., 2008 | 9 | | 2.6 | 33 | 7.9[d] |
| icebergs <3km: 1992-2012, >1Gt per 1° (lat) x 2° (long), total SO, in combination with tracked icebergs >5km | Tournadre *et al.,* 2013 with Stuart & Long, 2011 | 10, 11 | 3c | 19.91* | 69.9* | 28.47[a] |
| icebergs <3km: 1992-2012, >1Gt per 1° (lat) x 2° (long), on the shelf, in combination with tracked icebergs >5km | Tournadre *et al.,* 2013 with Stuart & Long, 2011 | 10, 11 | 3c | 1.82* | 61.3* | 2.97[e] |
| icebergs <3km: 1992-2012, area covered by icebergs <3km | Tournadre, this paper | | | 0.025* | 0.1* | 28.47[a] |
| icebergs <3km: 1992-2012, area covered by icebergs <3km plus 2km radius around | Tournadre, this paper | | | 0.31* | 1.1* | 28.47[a] |
| icebergs (all): iceberg area plus 2km radius around | Orheim, 1985; own assumptions | | | 0.49* | 1.7* | 28.47[a] |
| sea-bed area affected by iceberg scouring | Gutt & Starmans, 2001 | | | 1.31* | 44.1* | 2.97[e] |
| aragonite undersaturation, pelagic | Orr *et al.,* 2005 | 12 | 3d | 28.04 | 98.5 | 28.47[a] |
| aragonite undersaturation, all habitats (sea-floor & pelagic) | Orr *et al.,* 2005; Hauck *et al.,* 2010 | 12, 13 | 3d | 2.59 | 9.1 | 28.47 |

[a] entire SO

[b] sea-ice extent during the beginning of the melt period; in September (Comiso, 2010)
[c] ice shelf area 2002 (Clarke & Johnston 2003)
[d] average yearly sea-ice concentration (Bracegirdle et al. 2008)
[e] shelf area not beneath ice shelves (Clarke & Johnston, 2003)
* area potentially affected
** for cross-reference to figs 2-4.

## Supporting information legend

S1: Brief description of individual links between changes in the living and non-living nature of the Southern Ocean depicted in Fig. 1.

### *Interactions between changing environment and the sea-ice habitat*

The sea-ice biota is composed of a variety of small organisms, prokaryonts, protozoans, unicellular algae, and metazoans living inside the ice in brine channels; most if not all of them also occur in the open water (Deming, 2010). In addition, a number of apex predators stay for significantly important periods of their life on the ice, e.g. for resting, mating, birthing, and lactation and thus, also belong to the ice-associated community. Other macro- and microorganisms live in the ice covered open water at the subsurface of the sea-ice being closely or occasionally linked to it (Moline *et al.,* 2008). Life in the sea-ice is mainly shaped by sea-ice physics and biogeochemistry (1), which are driven by the atmosphere especially air temperature and wind (2). Numbers in parentheses refer to relationships in Fig. 1. The latter causes considerable divergent and convergent ice motion (Haas, 2010) with reverse feedback effects to the atmosphere, especially in terms of temperature and radiation, due to the high albedo and insulation quality of the ice (3). Also the ocean, especially its temperature, shapes physical processes in the sea-ice (4). Changes in the fauna and flora as well as nutrients in the ice are initially based on corresponding changes in the underlying water (5, 1). In addition, the ice quality especially resulting from differences in the formation processes and, consequently, in its thickness and age can be of high relevance for life in the ice (Meiners *et al.,* 2012). Independently of climate-induced changes, seasonal variations happen in most biological, physical and chemical variables (Ackley & Sullivan, 1994). Only micro- and macroorganisms living at the ice surface are directly exposed to the atmosphere. At ecological time scales changes in this exposition can happen if the cloud regime changes, in case of a shift in precipitation (e.g. from snow to rain), accumulation of iron from the atmosphere, in case of wind driven flooding, and when photosynthetically active radiation (PAR) changes (6) or when melting happens and melting ponds develop as a consequence of atmospheric warming (Willmes *et al.,* 2009), which is rare in the Antarctic compared to the Arctic (Drinkwater & Xiang, 2000). For the significance of the snow cover on sea-ice for ecological processes see Sturm & Massom (2010). Ice organisms, like those in the open water and on the sea-bed, consume and produce $CO_2$ as well as $O_2$ and the secondary metabolite dimethylsulphoniopropionate (DMSP), the precursor of the sulphurous gas dimethylsulfide (DMS). DMS is assumed to stimulate cloud formation and causing a cooling of the atmosphere (Trevena & Jones, 2006; Delille *et al*., 2007) and can also act as an important feedback system in the climate system. In essence, these algae respond to atmospheric changes, contribute to two of the perhaps most important ecosystem services, $CO_2$ uptake and $O_2$ production, and shape the climate system (7) (Charlson *et al.,* 1987). During the period of ice formation the complete inventory of species living later in the ice are potentially trapped from the open water (8) and with their specific development of their populations their species composition changes whilst nutrients decrease (Eicken, 1992; Arrigo *et al.,* 2010). Organisms living temporarily in or rather permanently linked to the habitat at the subsurface of the ice and in the platelet ice below the fast ice are potentially exposed to changes at the ocean-ice interface, especially referring to melting processes (9). This can affect algae, some fish species, copepods, krill (Bluhm *et al.,* 2010) and apex predators (Tynan *et al.,* 2010). Sea-ice distribution and dynamics are assumed to have impacts directly and indirectly through food-web changes on colony viability and breeding success of penguins (1,10) and some sea-birds (Jenouvrier *et al.,* 2005). Emperor penguin populations suffer in the slightly cooling East Antarctic (Jenouvrier *et al.,* 2009, Barber-Meyer *et. al.,* 2008, Barbraud *et al.,* 2011), whilst Adélie penguins increased in this region with more intensive marginal sea-ice (Trathan &

Ballard 2013). The ice-preferring Adélie penguins, however, decreased in the west of the Antarctic Peninsula due to changes in chlorophyll-a and krill biomass, those of chinstrap penguins due to unknown reasons (Lynch et al., 2012), whilst small populations of open-water preferring gentoo penguins increased in approximately the same area due to the loss of sea-ice. Also ice-depending seals are expected to be negatively affected by the decrease in sea-ice through a reduction of the (breeding-) habitat, crabeater and Weddell more, Ross and leopard seal less. Southern elephant and fur seals will respond in ways opposite to the pack ice species, but, as all seals, could also be influenced by changes in shifts in their forage basis (1,10) (Siniff *et al.,* 2008).

*Interactions with the pelagic*

Spatial and temporal changes in the sea-ice also shape physical processes in the ocean (11), e.g. heat and $CO_2$ exchange since it isolates (or shields?) the ocean from the atmosphere (3). During sea-ice formation the water column is destabilised by thermohaline convection (12, 13) and dense deep water is formed providing $O_2$ to the sea-floor on the shelf and in the deep-sea. In reverse, melting and also precipitation can cause a stratification of the upper water layer (12) being essentially important for the development of the phytoplankton bloom (14) (Arrigo *et al.,* 1999). Upwelling of warmer nutrient and carbon rich deepwater are wind-driven (15) and relate to the ozone depletion (Lenton *et al.,* 2013) or results from thermohaline convection (13) (Dinniman *et al.,* 2012). Temperature and pH closely interact with each other (16) and also with pressure, but only the first two of these parameters are climate-sensible.

The open water is the habitat of pelagic organisms ranging from drifting microorganisms (plankton) that contribute considerably to carbon, nutrient and energy cycles, to large gelatinous zooplankton and to mobile animals mostly representing higher trophic levels of which the great whales are the largest. They all are directly exposed to any changes in the ocean, especially in temperature, $CO_2$, and, as a consequence pH (17), which also shapes the food sources of the pelagic organisms, including sea-birds (Schofield *et al.,* 2010; Xavier *et al.,* 2013, Jenouvrier *et al.,* 2005). Ocean hydrodynamics also has an effect by acting as the transport vector for food, nutrients, drifting adult organisms (plankton) or developmental stages, e.g. eggs and larvae (14). For the high relevance of advection processes on krill, maybe as an example for many planktonic organisms see Hofmann & Murphy (2004). In case of elevated $CO_2$ concentrations phytoplankton assemblages are expected to potentially change their composition and increase population growth and, thus inducing feed-back processes on climate (Tortell *et al.,* 2008; 2009). Also interactions with the ozone hole (Tortell *et al.,* 2009) had been shown and with the availability of the micronutrient Fe in a long-term incubation experiment (Hoppe *et al.,* 2013). The ocean contributes to pH-related processes particularly biological $CO_2$ uptake through assimilation, especially by plants and respiration by animals life (18). Occasionally overseen in the context of climate change and its impact on the biosphere is an essential ecosystem service for most of the life on Earth, that is the production of $O_2$ by algae. This might increase in the SO due to upwelling processes (Arrigo *et al.,* 2008) and increased strength of stratification (14) (Sarmiento *et al.,* 2004). The ocean and sea-ice also physically interact with the atmosphere, notably through temperature and gas exchange, wind energy, fresh water (e.g. precipitation) and photosynthetically active radiation (PAR) transmission (2, 3, 15, 19, 20, 21).

As in all pelagic systems one of the most important drivers of live in the Southern Ocean (SO) is PAR. Changes in this variable can be expected only if changes in the protection shield happens, i.e. the ozone layer and cloud cover (22). The ice acts as a polar-specific shield at the interface between atmosphere and ocean (2, 1, 23).

In addition, elevated concentration of mineral particles in surface waters must be expected due to deglaciation and due to shifts in precipitation on land causing reduced light availability with consequences for primarily production (14) (Schloss *et al.,* 2014) and further through the food chain from krill up to whales (Grange & Smith, 2013). This can only happen where a true coast and a non-glaciated land-interior exists. The second main driver of primary production are nutrients. They can enter the ocean from the surface (15) (Ziegler *et al.,* 2013), be advectively transported or upwelled from the deep to shallower water layers (14). Especially for the SO, micronutrients seem to be of high relevance in addition to macronutrients (Blain *et al.,* 2007; Boyd *et al.,* 2012; Quéguiner, 2013). The main polar-specific and climate-driven factors of the pelagic system are the sea-ice dynamics (10) (Smith & Comiso, 2008), as well as the generally low ocean temperature (17).

Life in the open water can be seeded when sea-ice melts (Kuosa *et al.,* 1992) since some ice-algae contribute to the spring bloom of primary production (24) (Isla *et al.,* 2009) although this need not be necessary (Riebesell *et al.,* 1991). As organisms in the ice, like those in the open water, consume and produce $CO_2$ as well as $O_2$ and indirectly the climate gas DMS, thus, they do not only respond to atmospheric changes but contribute to a global atmospheric gas and energy budget (25).

Unique in the Antarctic are the large ice-shelves; their main ecological impact is that they block sun light and, thus, primary production in the water below them (23). Just like the sea-ice they are exposed to warming of the atmosphere (26) and the ocean (27), leading to regional collapse events, east and west of the Antarctic Peninsula (Vaughan & Spouge, 2002; Brachfeld *et al.,* 2003; Domack *et al.,* 2005b; Joughin & Alley, 2011). Both icebergs and cliffs shape current patterns and other small-scale hydrodynamic processes especially in the interplay with tides. Subsequently, they shape primary production in their surroundings by changing the nutrient regime (28) (e.g. Schwarz & Schodlok, 2009; Vernet *et al*., 2011; for review see Vernet *et al.,* 2012), which also happen in combination with the wind-driven sea-ice "behaviour" (29, 1) (Arrigo *et al*., 2002; Arrigo & van Dijken, 2003). These local processes change considerably in case of icebergs calving from the ice-shelf or glacier and their grounding on the shelf, as well as in case of larger disintegration events providing new space for primary production (23, 6, 22) (Cape *et al.,* 2014). This also provide a new habitat for additional pelagic species (30). Ice shelf basal melting can also affect sea-ice expansion (29, Bintanja *et al.,* 2013)

Increased UV radiation as a consequence of ozone hole formation in early spring affects directly all shallow water habitats (6, 22, 31).

*Interactions with the benthic habitat*

When ice shelves and floating glaciers tongues disintegrate major changes in the water column happen (28) (Nicholls *et al*., 2009). PAR starts to penetrate into the ocean (23) and supports primary production (Peck *et al.,* 2009b; Cape *et al.,* 2014) with important consequences for the benthic life. A strong increase in the growth of populations initially of pioneer species, later of a larger variety of species can be expected (Gutt *et al.,* 2011, 2013). Deep-sea species assumed to belong to the ice-covered oligotrophic situation are assumed to suffer in the long run.

When ice-shelves collapse, icebergs are produced, drift in the circumpolar current and occasionally run aground or scour the sea-bed (32). This happens mostly down to 250 m but in rare cases also to a maximum of 600 m, where the icebergs shape the intermediate- and small-scale bottom topography (33) (Viehoff & Li, 1995; Harris & O'Brien, 1996). Depressions of up to 25 m depth are formed, elevations thrown up, sediments mixed and resorted and nutrients released as well as organic matter resuspended (28). In shallow water similar effects are caused by the sea-ice, especially where ice is ridged or anchor ice is formed (34) (Dayton *et al.,* 1970). The main ecological impact is the devastation of the sea-floor inhabiting fauna (35), in rare cases living organisms can be dislocated (Dayton, 1989; Seiler & Gutt, 2007). Subsequently, the scoured areas provide a pristine substratum for new benthic colonisation. The resulting patterns of different co-existing successional stages are known to have an increased diversity compared to relatively stable and mature communities (Gutt & Piepenburg, 2003). Model-based simulations of the benthic succession after iceberg disturbance on the shelf show that only a strong increase in disturbance would lead to a decreased diversity (Johst *et al.,* 2006). Following the Intermediate-Disturbance-Hypothesis (Connell, 1978), a decrease in disturbance magnitude would lead to a reduced benthic biodiversity because populations of pioneer organisms, which benefit from the lack of competition in the devastated areas, would suffer. The actual disturbance intensity is that 1 $m^2$ is devastated once in 340 years (Gutt, 2001). In addition, a changing bottom-near current regime resulting from an increased complexity of the sea-bed morphology due to iceberg scouring (33, 36) might support a more patchy distribution of organisms (37). The new sorting of sediment has potentially also an effect (38, 39), however, in the Antarctic this might not be severe since benthic communities seem to be only weakly related to specific grain sizes (Gutt, 2000; Cummings *et al.,* 2006). All components of the benthos, the micro-, meio- and macrofauna as well as micro- and macroalgae are also potentially exposed to changes in the bottom-near waters at any depths, especially warming (40), acidification (41) and support of food and nutrients (37). The pace of acclimatisation also seems to play an important role (Peck *et al.*, 2014). Maybe an adaptation to acidification otherwise considered as harmful to calcifying organisms is possible (Cohen *et al.,* 2009). The flora and fauna respond especially to changes in the light regime (31), eventually even with a substantial regime shift (Clark *et al.,* 2013), in addition, like microalgae, they shape the chemical composition of the atmosphere (42) especially by $CO_2$ uptake and production of DMSP. Since benthic animals do not only depend directly on phytodetritus but also on faecal pellets, dead or living zooplankton and large carcasses, the benthos is also closely linked to the secondary production in the pelagic (43). Small changes in temperature can change the behaviour of water masses (Fahrbach *et al.,* 2011; Purkey & Johnson, 2011). It can for example reduce the ventilation of the deep-sea with oxygen- and nutrient-rich water (Orsi *et al.,* 1995; Primeau *et al.,* 2013), which could cause significant indirect impact to the deep-sea fauna. At a world-wide scale the loss of the great whales is considered to affect biological processes at the sea-floor especially with respect to biodiversity (Jelmert & Oppen-Bernsten, 1996). In the Antarctic, major changes must be expected in case of a shift in the pelagic from a krill to a salp or copepod dominated system with changing quality and quantity of them as food supply for higher trophic levels and their faecal pellets sinking to the sea-bed. In general similar effects can be expected in case of a shift from larger to smaller plankton organisms (Moline *et al.,* 2004). As a consequence of whaling, also in the Antarctic an important reduction of whale faeces and carcases reaching the sea-floor may have happened. Increased turbidity in the water following deglaciation on land might damage vitally important feeding process of epibenthic filter feeders (Gutt *et al.,* 2011). The benthos including all fractions, of micro-, meio- and macrofauna contributed significantly to remineralisation (44).