

# Polar Regions

## Supplementary Material

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### This chapter supplementary material should be cited as:

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions Supplementary Material. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Available from <https://www.ipcc.ch/srocc/>.

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## SM3.1 Polar Regions, People and the Planet

### SM3.1.1 Northern Hemispheric Climate Modes

The Northern Hemisphere atmospheric wind motion is primarily a zonal jet stream that includes multiple north-south meandering wave patterns. Recurring climate patterns can also be described using modes of atmospheric variability. The most important patterns for the Northern Hemisphere climate are centred on the North Pole, the North Atlantic, and the North Pacific.

The Arctic Oscillation (AO) or Northern Annular Mode in its positive sign has zonal symmetric flow centred on the North Pole. In its negative phase this pattern breaks down into a weaker and wavier circulation pattern. The North Atlantic Oscillation (NAO) is an Atlantic extension of the AO with a positive phase for lower pressure near Iceland (Thompson and Wallace, 1998).

The pattern in the North Pacific is either captured by the Pacific North American (PNA) pattern based on the height of constant pressure surfaces above the ground level (geopotential height) or the Pacific Decadal Oscillation (PDO) based on ocean temperature. Positive phase is associated with lower pressures in the Aleutian low pressure region and positive temperature anomalies in the Gulf of Alaska.

Another pattern of interest is the Arctic Dipole (AD), which is the third hemispheric pattern. In contrast to the AO that is circular around a given latitudinal, the AD has flow across the central Arctic with high and low pressures on either side (Asia and North America).

The historical time series of all these patterns have interannual and multi-year variability that is mostly internal atmospheric stochastic variability rather than driven by external forcing such as greenhouse gas warming. The cause of multi-year persistence to these patterns is not well understood. The winter AO was negative up to the late 1980s (except for the early 1970s), had a large positive sign in the early 1990s, and is mostly variable since then. The PNA/PDO had a large shift in the mid-1970s and is variable and slightly positive since then. The NAO was also positive in the 1990s and variable since then. The NAO had an extreme negative winter in 2010 and an extreme positive winter in 2015. In the early 2000s a strong AD helped to reinforce summer sea ice loss (Wang et al., 2009). Since the IPCC 5th Assessment Report (AR5) much variability in Northern Hemispheric atmospheric modes remains driven by internal atmospheric processes (*medium confidence*).

### SM3.1.2 Arctic Amplification

The impacts of global warming are strongly manifested in the polar regions because increases in air temperature lead to reductions in snow and ice, allowing more of the sun's energy to be absorbed by the surface, fostering more melt (Manabe and Stouffer, 1980; Overland et al., 2017) (Box 3.1). Furthermore, increased exchanges of latent heat flux from the ocean to the atmosphere have led to increased atmospheric water vapour which contributes to further warming (Serreze et al., 2012). The sea ice albedo feedback has

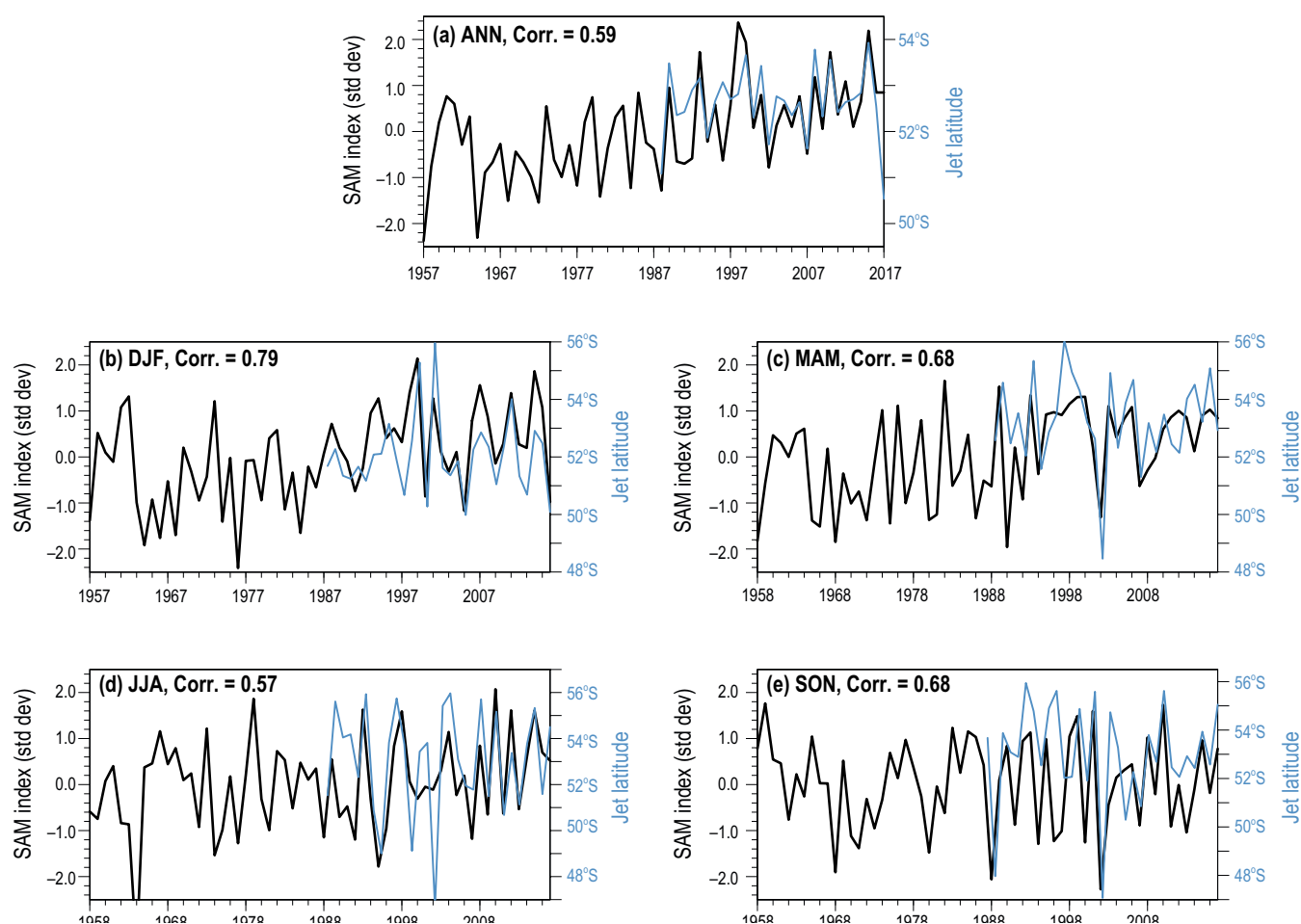
been implicated in dramatic sea ice loss events (Perovich et al., 2008) and in the observed Arctic amplification of warming trends (Serreze et al., 2009; Screen and Simmonds, 2010; Taylor et al., 2013) (*very high confidence*).

Modelling studies show that Arctic amplification is related to the observed transition from perennial to seasonal sea ice (Haine and Martin, 2017), but it can still occur in the absence of the sea ice albedo feedback (Alexeev et al., 2005) because of the contributions from other processes. There is emerging evidence of increased warm, moist air intrusions in both winter and spring (Boisvert et al., 2016; Cullather et al., 2016; Kapsch et al., 2016; Mortin et al., 2016; Graham et al., 2017). Tropical convection may play a role by exciting these intrusion events on inter-decadal time scales (Lee et al., 2011). Intra-seasonal tropical convection variability may influence daily Arctic surface temperatures in both summer and winter (Yoo et al., 2012a; Yoo et al., 2012b; Henderson et al., 2014). The intrusion of weather events into the Arctic from the subarctic lead to increased downwelling longwave radiation from a warmer free troposphere as well as from increased atmospheric moisture. A large contributor to Arctic amplification is increased downwelling longwave radiation (Pithan and Mauritsen, 2014; Boeke and Taylor, 2018). It is important to recognize the contributions from both local forcing (i.e., ice albedo feedback, increased atmospheric water vapour and cloud cover) from remote forcing (i.e., changes in atmospheric circulation).

### SM3.1.3 Southern Hemispheric Climate Modes

Observed changes in the Southern Hemisphere extratropical atmospheric circulation are primarily indicated by the Southern Annular Mode (SAM), the leading mode of extratropical variability in sea level pressure or geopotential heights, which is related to the latitudinal position and strength of the mid-latitude eddy-driven jet (Thompson and Wallace, 2000). In winter and spring these winds exhibit more zonal asymmetries, expressed by the zonal wave 3 (ZW3) (Raphael, 2004) and Pacific South American (PSA) patterns (Irving and Simmonds, 2015). Understanding decadal variability, such as the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation's (PDO/IPO) impact on these modes is hampered by the shortness of the observational record, with limited station data available poleward of 40°S (Marshall, 2003).

The SAM has a strong influence on the weather and climate of Southern Hemisphere polar regions as well as southern Australia, New Zealand, southern South America and South Africa (see review article by Thompson et al. (2011)). Numerous studies have attributed a significant positive trend in the summertime SAM over the past 30–50 years to anthropogenic forcing, in particular stratospheric ozone depletion and increasing greenhouse gases (Gillett et al., 2013) (Figure SM3.1). Though the exact mechanisms by which these forcings impact the circulation is unclear, they both act to enhance the meridional temperature gradient which leads to a poleward shift in the Southern Hemisphere extratropical circulation. There is *medium confidence* that ozone depletion is the dominant driver of recent austral summer changes in the Southern Hemisphere circulation during the period of maximum ozone depletion from the

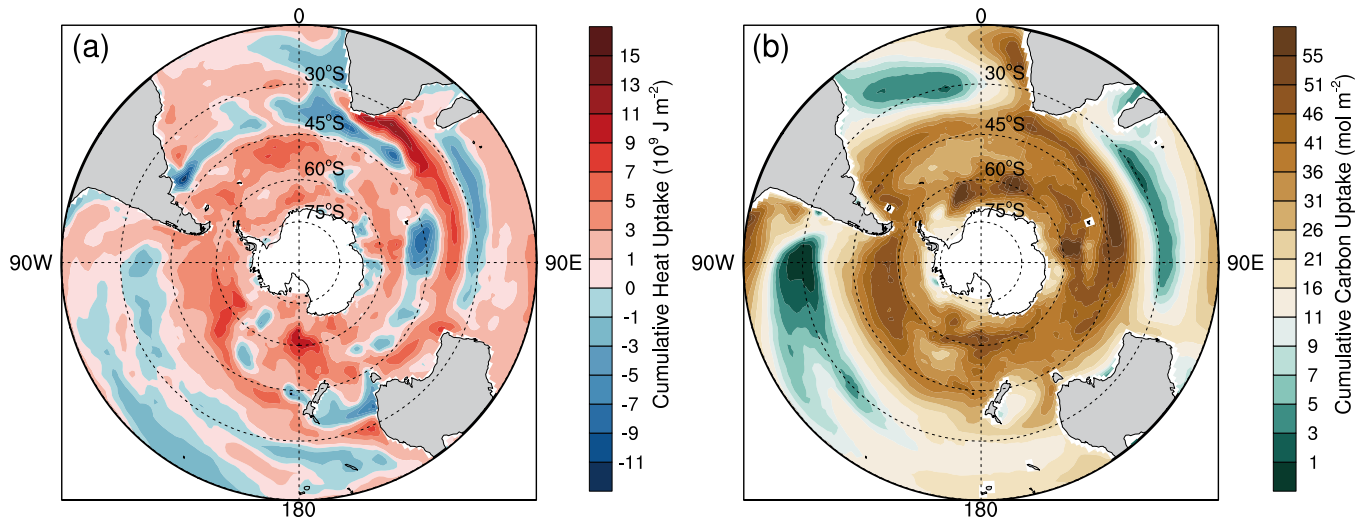


**Figure SM3.1** | Southern Annular Mode (SAM) index (black) and mid-latitude jet positions (blue) time series for (a) annual mean (ANN) and (b–e) the four seasons December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON). The SAM index (Marshall (2003); available for download from <http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.1957.2007.seas.txt>) is normalized by its standard deviation. The jet position is based on the maximum of Cross-Calibrated Multi-Platform satellite-based surface wind speed (Atlas et al. (2011); available for download at <http://www.remss.com/measurements/ccmp.html>) which starts in 1987. Statistically significant trends in the SAM over the time period shown are found for the annual mean, December to February and March to May. No statistically significant trends are found for the jet position over the shorter period for which it is available. Adapted from Karpechko and Maycock (2018).

late 1970s to late 1990s (Arblaster et al., 2014; Waugh et al., 2015; Karpechko and Maycock, 2018). In the years following, Waugh et al. (2015) and other studies argue for a strong impact of tropical Pacific sea surface temperatures in driving positive SAM trends (Schneider et al., 2015; Clem et al., 2017).

ZW3 describes the asymmetric part of the generally strongly zonally symmetric circulation in the Southern Hemisphere extratropics and has been shown to impact the Southern Hemisphere surface climate, blocking, sea ice extent and the strength of the Amundsen Sea Low (Turner et al., 2017b; Schlosser et al., 2018). It has its strongest amplitude in Southern Hemisphere winter and is more prominent during phases of negative SAM (Irving and Simmonds, 2015). No significant trends in the amplitude or phase of ZW3 over the satellite era have been found (Turner et al., 2017a).

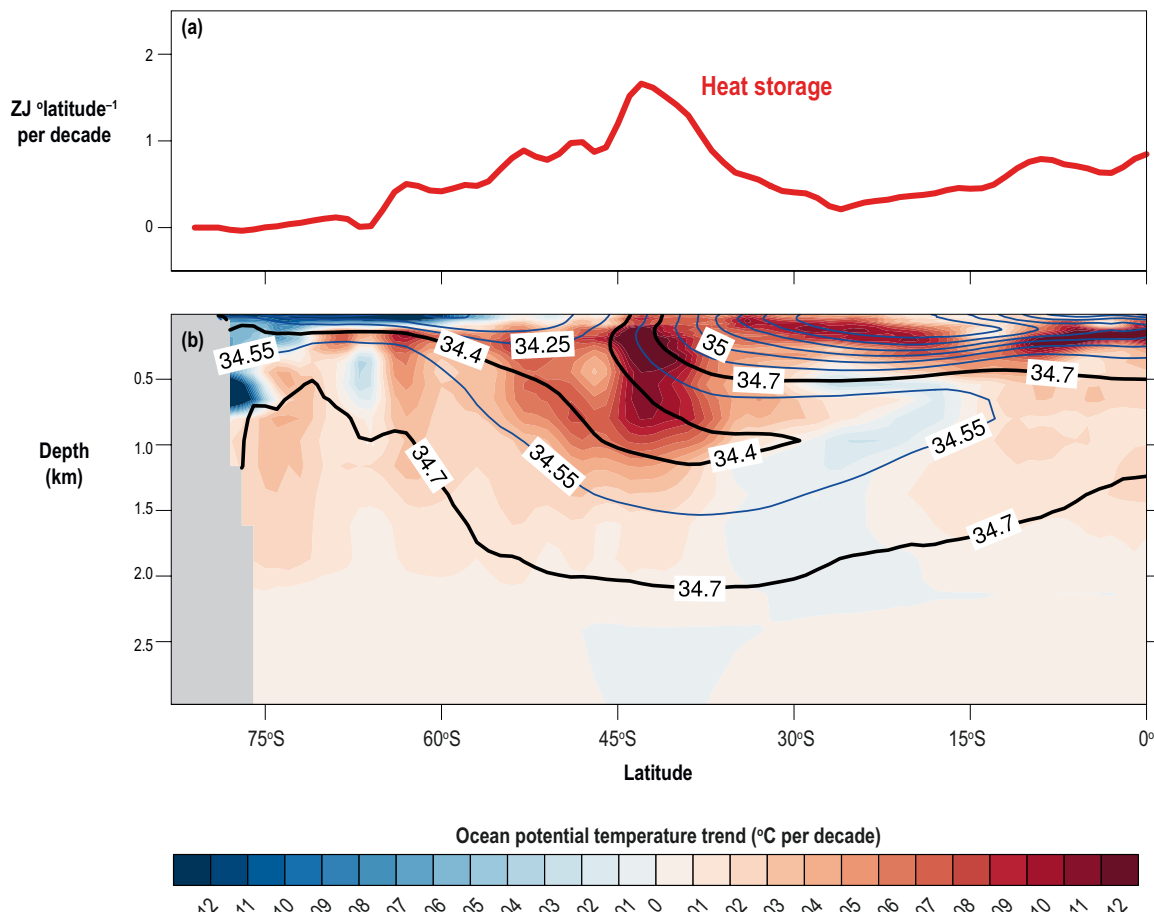
The PSA pattern reflects a Rossby wave train from the tropical Pacific and is the primary mechanism by which tropical Pacific sea surface temperatures, including the El Niño Southern Oscillation, impact the Antarctic climate (Mo and Higgins, 1998; Irving and Simmonds, 2016). It has been shown to be closely related to the Amundsen Sea Low and to have a strong influence on temperature and precipitation variability of West Antarctica and the Antarctic Peninsula (AP) as well as sea ice in the Amundsen, Bellingshausen and Weddell Seas (Irving and Simmonds, 2016; Pope et al., 2017). The PSA has experienced a trend towards its more negative phase over the satellite era (Irving and Simmonds, 2016), consistent with a deepening of the Amundsen Sea Low (Schneider et al., 2015; Raphael et al., 2016), however there is *low confidence* in these trends and their attribution given the large internal variability in this region and shortness of the observational record.



**Figure SM3.2** | Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel mean changes in depth-integrated oceanic heat **(a)** and anthropogenic carbon **(b)** between 1870 (represented by mean of period 1861–1880) and 1995 (represented by mean of period 1986–2005). In these models, the Southern Ocean accounts for  $75 \pm 22\%$  of the total global ocean heat uptake and  $43 \pm 3\%$  of anthropogenic  $\text{CO}_2$  uptake (Frölicher et al., 2015).

## SM3.2 Implications of Climate Change for Polar Oceans and Sea Ice: Feedbacks and Consequences for Ecological and Social Systems

### SM3.2.1 Heat and Carbon Uptake by the Southern Ocean



**Figure SM3.3** | **(a)** Zonally- and depth-integrated ocean heat content trends from EN4 datasets (<https://www.metoffice.gov.uk/hadobs/en4/>), for period 1982–2017. **(b)** Zonal mean ocean potential temperature trend (shading) from EN4 for 1982–2017, with climatological ocean salinity in intervals of 0.15 (contours). Updated from Armour et al. (2016).

**Table SM3.1** | Ocean heat content trend (0–2000 m depth) during 1970–2017 using the Ordinary Least Square method. Units are  $10^{21} \text{ J yr}^{-1}$ . Values in curved brackets denote the proportion of heat storage in the Southern Ocean compared to the global ocean. Quoted uncertainties denote the 90% confidence interval. Data sources are Ishii (Ishii et al., 2017), IAP (Cheng et al., 2017), EN4 (Good et al., 2013), and updates thereof. The mean proportion and its 5–95% confidence interval (1.65 times standard deviation of individual estimates) are provided in the bottom row.

Region	South of 20°S	South of 30°S	South of 35°S	South of 40°S	Global
% of global ocean area	33%	25%	21%	18%	100%
OHC Trend ( $10^{21} \text{ J yr}^{-1}$ ):					
Ishii V7.2	$2.83 \pm 0.28$ (42%)	$2.42 \pm 0.26$ (36%)	$2.10 \pm 0.22$ (31%)	$1.63 \pm 0.16$ (24%)	$6.73 \pm 0.55$
IAP	$3.16 \pm 0.34$ (45%)	$2.78 \pm 0.29$ (40%)	$2.50 \pm 0.28$ (36%)	$1.99 \pm 0.24$ (28%)	$7.02 \pm 1.96$
EN4-GR10	$2.32 \pm 0.42$ (44%)	$2.18 \pm 0.36$ (41%)	$2.05 \pm 0.32$ (39%)	$1.73 \pm 0.24$ (33%)	$5.28 \pm 1.01$
Mean [5%, 95%]	<b>44%</b> [41%, 46%]	<b>39%</b> [35%, 43%]	<b>35%</b> [29%, 42%]	<b>28%</b> [21%, 36%]	

**Table SM3.2** | Ocean heat content trend (0–2000 m depth) during 2005–2017 using the Ordinary Least Square method. Units are  $10^{21} \text{ J yr}^{-1}$ . Values in curved brackets denote the proportion of heat storage in the Southern Ocean compared to the global ocean. Quoted uncertainties denote the 90% confidence interval, taking into account the reduction in the degrees of freedom implied by the temporal correlation of the residuals. Data sources are as per Table SM3.1, plus IPRC (2015) (<http://apdrc.soest.hawaii.edu/projects/argo/>), Scripps (Roemmich and Gilson, 2009), JAMSTEC (Hosoda et al., 2011) and updates thereof. The mean proportion and its 5–95% confidence interval (1.65 times standard deviation of individual estimates) are provided in the bottom row.

Region	South of 20°S	South of 30°S	South of 35°S	South of 40°S	Global
% of global ocean area	33%	25%	21%	18%	100%
OHC Trend ( $10^{21} \text{ J yr}^{-1}$ ):					
Ishii V7.2	$5.90 \pm 1.19$ (59%)	$5.20 \pm 1.03$ (52%)	$4.29 \pm 0.84$ (43%)	$3.10 \pm 0.54$ (31%)	$10.06 \pm 1.28$
IAP	$5.10 \pm 1.13$ (60%)	$4.55 \pm 1.00$ (54%)	$3.96 \pm 0.81$ (47%)	$3.10 \pm 0.58$ (37%)	$8.45 \pm 1.04$
EN4-GR10	$6.08 \pm 1.24$ (58%)	$5.38 \pm 1.30$ (51%)	$4.56 \pm 1.19$ (43%)	$3.22 \pm 0.88$ (30%)	$10.57 \pm 1.17$
IPRC	$6.92 \pm 2.03$ (69%)	$6.24 \pm 1.80$ (63%)	$5.34 \pm 1.51$ (54%)	$3.41 \pm 1.19$ (34%)	$9.96 \pm 1.57$
Scripps	$4.73 \pm 0.79$ (56%)	$4.22 \pm 0.70$ (50%)	$3.64 \pm 0.60$ (43%)	$2.66 \pm 0.46$ (32%)	$8.38 \pm 1.31$
JAMSTEC	$5.05 \pm 0.78$ (56%)	$4.44 \pm 0.63$ (49%)	$3.79 \pm 0.54$ (42%)	$2.69 \pm 0.38$ (30%)	$9.06 \pm 0.67$
Mean [5%, 95%]	<b>60%</b> [52%, 68%]	<b>53%</b> [45%, 62%]	<b>45%</b> [38%, 53%]	<b>32%</b> [28%, 37%]	

**Table SM3.3** | As per Table SM3.1, but for ocean heat content trends (0–2000 m depth) during 1970–2004.

Region	South of 20°S	South of 30°S	South of 35°S	South of 40°S	Global
% of global ocean area	33%	25%	21%	18%	100%
OHC Trend ( $10^{21} \text{ J yr}^{-1}$ ):					
Ishii V7.2	$2.10 \pm 0.32$ (40%)	$1.74 \pm 0.28$ (33%)	$1.49 \pm 0.24$ (28%)	$1.13 \pm 0.18$ (21%)	$5.28 \pm 0.63$
IAP	$2.59 \pm 0.44$ (48%)	$2.40 \pm 0.42$ (45%)	$2.21 \pm 0.43$ (41%)	$1.78 \pm 0.40$ (33%)	$5.32 \pm 1.01$
EN4-GR10	$0.85 \pm 0.37$ (37%)	$0.99 \pm 0.32$ (43%)	$1.04 \pm 0.31$ (44%)	$0.94 \pm 0.24$ (40%)	$2.33 \pm 0.90$
Mean [5%, 95%]	<b>42%</b> [32%, 51%]	<b>40%</b> [30%, 51%]	<b>38%</b> [24%, 52%]	<b>31%</b> [15%, 47%]	



### SM3.2.2 Stratification

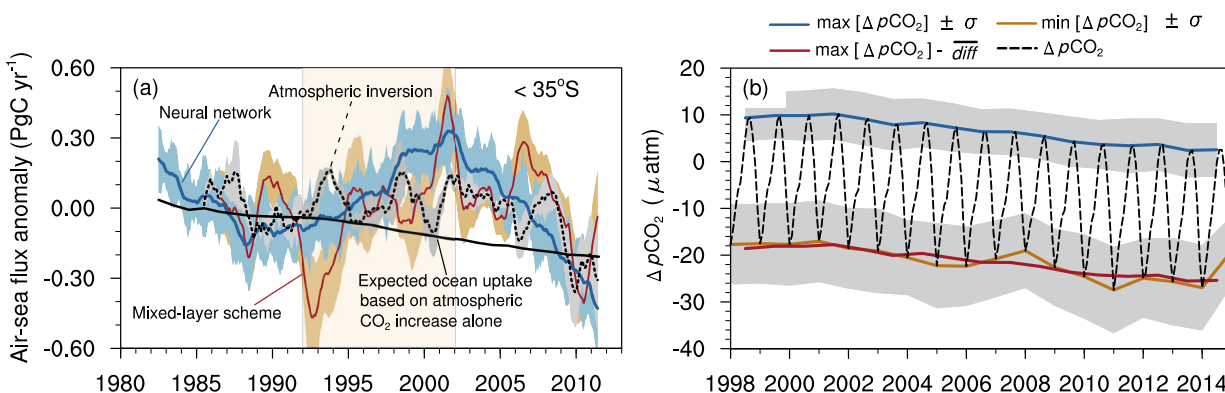
Changing stratification in the polar oceans is of key significance to climate and ecosystems. Upper-ocean stratification mediates the transfer of heat, salt and nutrients between the surface ocean and the ocean interior, and is an important factor in determining the rates and distributions of marine primary production.

Arctic Ocean stratification is strongest at the base of the surface mixed layer, with mixed-layer depths ranging around 25–50 m in winter and around 5–30 m in summer (Peralta-Ferriz and Woodgate, 2015). General trends between 1979 and 2012 across the entire central Arctic over all seasons, and in the winter in the boundary regions (Chukchi, southern Beaufort and Barents seas) indicate a mixed layer shoaling of about 0.5–1 m yr<sup>-1</sup>, with mixed-layer deepening trends

evident in some regions (e.g., the southern Beaufort Sea in summer; Peralta-Ferriz and Woodgate, 2015). Shoaling has been attributed to surface ocean freshening and inhibition of mixed-layer deepening by convection and shear driven mixing, whilst deepening trends have been attributed to winds that drive offshore transport of surface freshwater (Peralta-Ferriz and Woodgate, 2015). The Atlantification in the Eurasian Basin is associated with weakening stratification in the eastern Eurasian Basin at the top boundary of the Atlantic Water Layer from 2012 to 2016, related to reduced sea ice cover and increased vertical mixing (Polyakov et al., 2017).

For the Southern Ocean, there is only *limited evidence* for stratification changes in the post-AR5 period. Section 3.3.3 assesses the potential of freshwater discharge from the Antarctic Ice Sheet (AIS) to influence such stratification.

### SM3.2.3 Decadal Variability in the Southern Ocean Air-sea Flux of CO<sub>2</sub>



**Figure SM3.4** | (a) Decadal variability in the Southern Ocean air-sea CO<sub>2</sub> flux anomaly (adapted from Landschützer et al. (2015)). Curves contrast the decadal model reconstruction (1982–2012) of CO<sub>2</sub> air-sea flux anomalies from observations and neural network against a second empirical method (Rodenbeck et al., 2014) and a model-based steady-state linear trend of an increasing CO<sub>2</sub> sink. Yellow shading denotes the period of the weakening of the Southern Ocean carbon sink, separating periods of strengthening before and after. (b) The interannual variability of the seasonal cycle of ΔpCO<sub>2</sub> showing that the decadal trend (1998–2012) is strongly associated with trends in winter peaks of ΔpCO<sub>2</sub>, whereas the summer minima have stronger interannual modes. σ denotes 1 standard deviation. (Adapted from Gregor et al. (2017)).

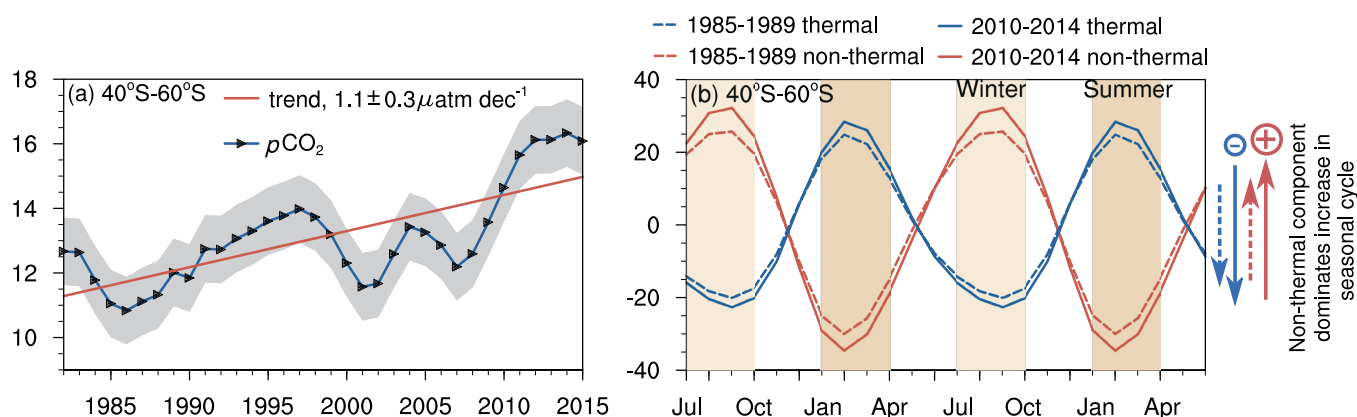
### SM3.2.4 Variability and Trends in DIC Buffer Factor (γ)

The Dissolved Inorganic Carbon (DIC) buffer factor (γ) reflects the sensitivity of changing ocean pCO<sub>2</sub> to a changing DIC (Eggleston et al., 2010). The Revelle Factor is the reciprocal of γ, i.e. Revelle Factor = 1/γ. Decreasing buffer factor (or increasing Revelle Factor) with rising atmospheric pCO<sub>2</sub> linked to anthropogenic emissions acts as a strong positive feedback on atmospheric CO<sub>2</sub>, by reducing potential future uptake of CO<sub>2</sub> by the Southern Ocean (Wang et al., 2016). The Revelle Factor will grow to become one of the most important factors reducing the capacity of the Southern Ocean to take up anthropogenic CO<sub>2</sub> (Eggleston et al., 2010) and play a positive feedback role in the carbon-climate system as well as early onset of hypercapnia or carbonate under saturation (McNeil and Sasse, 2016; Kwiatkowski and Orr, 2018).

One of the important outcomes predicted by carbonate equilibrium theory for a decreasing buffering capacity is an amplified seasonal variability of pCO<sub>2</sub> (Eggleston et al., 2010; McNeil and Sasse, 2016). A century-scale set of model runs comparing the Representative

Concentration Pathway (RCP)8.5 scenario with a control (constant at pre-industrial pCO<sub>2</sub>) showed that the seasonal cycle of pCO<sub>2</sub> amplified by a factor of 2–3 mainly due to the increased sensitivity of CO<sub>2</sub> to summer DIC drawdown by primary productivity (Hauck and Volker, 2015). Thus in future, as buffering capacity of the ocean decreases towards the end of the century, biology will have an increased contribution to the uptake of anthropogenic carbon during the summer in the Southern Ocean (Hauck and Volker, 2015).

This has been further investigated using observation-based CO<sub>2</sub> products (Landschützer et al., 2018). Using the data product that spans 34 years (1982–2015) the study confirms the model predictions that there already exists an observable trend in the increase of the mean seasonal amplitude of the seasonal cycle of pCO<sub>2</sub> of 1.1 ± 0.3 μatm per decade in the Southern Ocean (Landschützer et al., 2018) (Figure SM3.5a). It also shows that this mean trend is the net effect of opposing contributions from biogeochemical (non-thermal) (2.9 ± 0.7) and thermal (–2.1 ± 0.5) forcings (Figure SM3.5b). Thermal forcing refers to forcing from changes in sea surface temperature driven by heat uptake or circulation changes. Biogeochemical or



**Figure SM3.5 |** (a) The significant multi-decadal (1982–2005) trend ( $1.1 \pm 0.3$   $\mu\text{atm}$  per decade) in increasing amplitude of the seasonal cycle of  $\text{pCO}_2$  in the Southern Ocean. (b) The seasonal trend signal decomposed for thermal and non-thermal drivers: non-thermal dissolved inorganic carbon (DIC) drivers dominate the trend. Adapted from Landschützer et al. (2018).

non-thermal forcing refers to seasonal primary productivity and mixing or entrainment. Overall, these changes to the characteristics of the seasonal cycle of biogeochemistry and CO<sub>2</sub> because of the trends in reduced buffering will become dominant drivers of the long-term trend of the fluxes and storage of anthropogenic CO<sub>2</sub> in the Southern Ocean (Hauck and Volker, 2015; McNeil and Sasse, 2016).

2017) (Table SM3.4). The net carbon storage is largely influenced by changes in the elevated natural CO<sub>2</sub> derived from DIC-rich deep ocean waters that have not had contact with the atmosphere since the start of the industrial period. This has the potential to explain why storage increases when upper-ocean overturning weakens and outgassing is reduced (DeVries et al., 2017). In contrast, anthropogenic carbon has maximum storage during high upper-ocean overturning periods, probably due to its sensitivity to the increased rate of subduction of mode and intermediate waters (Tanhua et al., 2017). The magnitude of the carbon storage variability is therefore an indication of the sensitivity of the system to small wind driven adjustments in the upper-ocean overturning circulation (Swart et al., 2014; Swart et al., 2015).

### SM3.2.5 Decadal Changes in Southern Ocean Carbon Storage Rates

Decadal changes in the modelled net carbon and observed anthropogenic carbon storage rates may be linked to the decadal phases of the upper-ocean overturning circulation (DeVries et al.,

**Table SM3.4 |** Comparison of the phasing and magnitude of the decadal variability in net carbon and anthropogenic carbon storage in the Southern Ocean (DeVries et al., 2017; Tanhua et al., 2017). UOOC is Upper-Ocean Overturning Circulation;  $C_{ANT}$  is anthropogenic carbon.

Decade	DeVries et al. (2017)		Tanhua et al. (2017)	
	Net storage CO <sub>2</sub>	Explanation	C <sub>ANT</sub> Storage Rates	Explanation
1980s	High: 0.53 Pg C yr <sup>-1</sup>	Slow UOOC: outgassing reduced – storage increased	1984–1990 440 kmol yr <sup>-1</sup> m <sup>-1</sup>	Lower storage in mode waters
1990s	Low: 0.20 Pg C yr <sup>-1</sup>	Faster UOOC: outgassing increased – storage reduced	1984–2005 1142 kmol yr <sup>-1</sup> m <sup>-1</sup>	High storage in mode waters
2000s	High: 0.61 PgC yr <sup>-1</sup>	Slow UOOC: outgassing decreased – storage increased	2005–2012 –752 kmol yr <sup>-1</sup> m <sup>-1</sup>	Lower storage in intermediate waters

**Table SM3.5** | Timing of the onset of monthly and annual-mean undersaturation in the Southern Ocean under different emission scenarios. The effect of the abrupt change threshold between Representative Concentration Pathway (RCP)2.6 and RCP4.5/RCP8.5 is apparent. Although all scenarios show an onset of month-long undersaturation in the 21st century, the area covered by this condition under RCP2.6 is 0.2% of that covered by RCP8.5 (Sasse et al., 2015).

Scenario	Onset of month-long undersaturation	Onset of annual undersaturation	% Impact area relative to RCP8.5
RCP8.5	2048 ± 15	10–20	–
RCP4.5	2073 ± 17	10–20	
RCP2.6	2033 ± 15	None	0.2%



### SM3.2.6 Climate Change Impacts on Arctic Kelp Forests

In the Arctic, biodiversity of macroalgae and biomass of kelps and associated fauna have considerably increased in the intertidal to shallow subtidal zone over the last two decades, causing changes in the food web structure and functionality. This is mostly accounted for by reduced physical impact by ice scouring and increased light availability as a consequence of warming and concomitant fast ice retreat (Kortsch et al., 2012; Bartsch et al., 2016; Paar et al., 2016) (*medium confidence*). Increase of summer seawater temperatures up to 10°C (IPCC 2100 scenario) will not be detrimental for Arctic kelp species. A further seawater temperature increase above 10°C which is only expected under extreme warming scenarios will definitely suppress the abundance, growth and productivity of Arctic endemic *Laminaria solidungula* and sub-Arctic *Alaria esculenta* but not of cold-temperate to Arctic *L. digitata* and *Saccharina latissima* (Dieck, 1992; Gordillo et al., 2016; Roleda, 2016; Zacher et al., 2016) (*high confidence*). In total, these data support projections that kelp and macroalgal production will increase in the future Arctic (e.g., Krause-Jensen et al., 2016). This will become more pronounced when rocky substrates hidden in current permafrost areas (Lantuit et al., 2012) become readily colonized by kelp and other macroalgae during their transition toward ice-free conditions, as has been verified for Antarctica (Liliana Quartino et al., 2013; Campana et al., 2017) (*high confidence*).

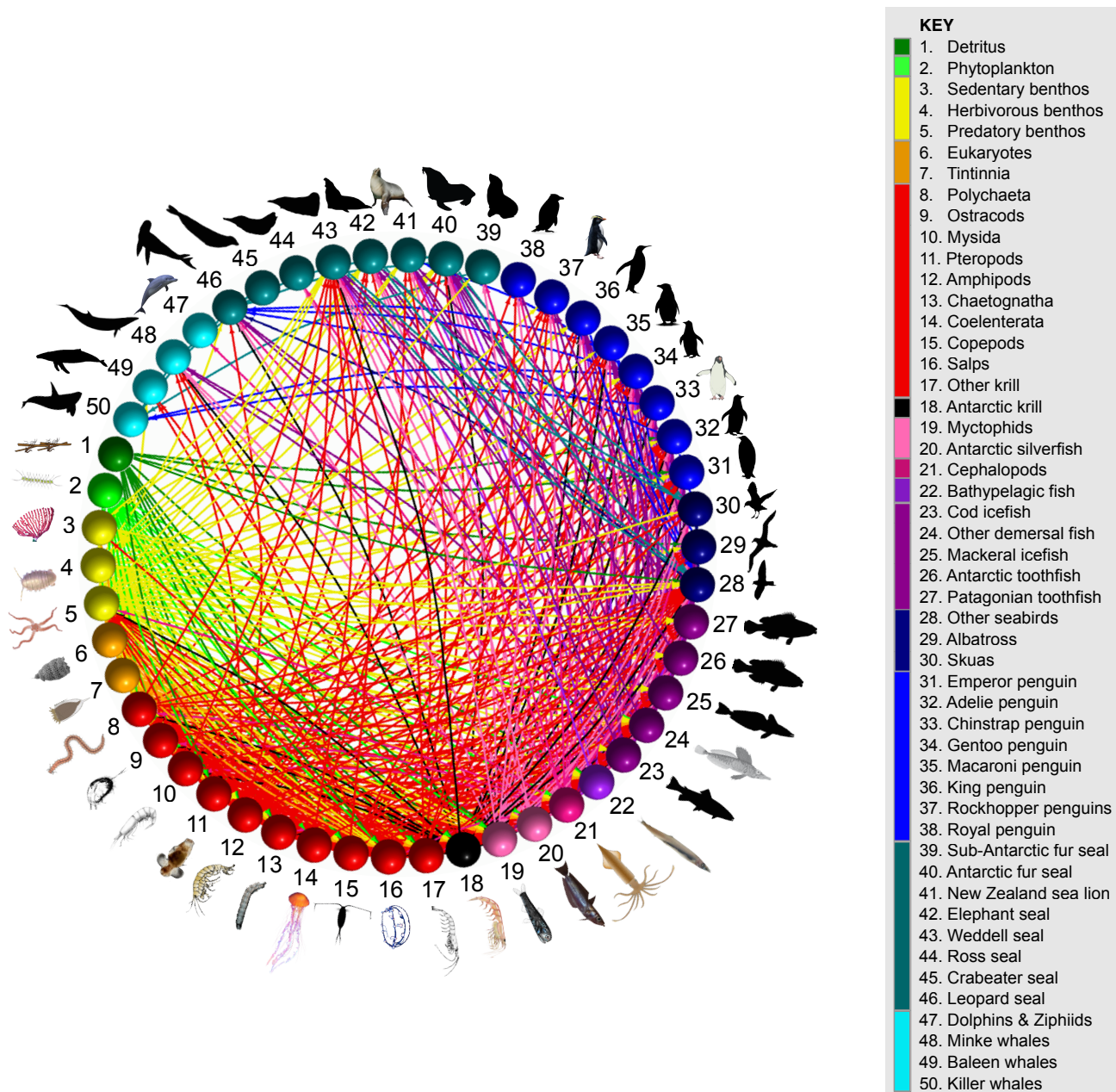
Besides the direct effects of temperature, sedimentation is a major driver in fjord systems influenced by glaciers. The reduced depth extension of several kelp species in Kongsfjorden between 1986 and 2014 was attributed to overall increased turbidity and sedimentation (Bartsch et al., 2016). Sedimentation may also inhibit the germination of Arctic kelp spores and reduce their subsequent sporophyte recruitment (*Alaria esculenta*, *Saccharina latissima*, *Laminaria digitata*). Interaction with grazing and a simulated increase in summer sea temperatures by 3°C–4°C (scenario for 2100) partially counteracts the negative impact of sedimentation in a species-specific manner (Zacher et al., 2016). Transient sediment cover on kelp blades on the other hand provides an effective shield

against harmful ultraviolet radiation (Roleda et al., 2008). Glacial melt also increases freshwater inflow into Arctic fjord systems and thereby may impose hyposaline conditions to shallow water kelps. Pre-conditioning with low salinity as a stressor results in an increased tolerance towards UV radiation in Arctic *A. esculenta*, thereby indicating the potential of cross-acclimation under environmental change (Springer et al., 2017).

Ocean acidification in interaction with climate warming will be most pronounced in the Arctic, where kelp and kelp-like brown algae show variable species-specific responses under end of the century scenarios for CO<sub>2</sub> (390 and 1000 ppm) and temperature (4°C and 10°C) (Gordillo et al., 2015; Gordillo et al., 2016; Iñiguez et al., 2016). On the biochemical side, warming involves photochemistry adjustments while increased CO<sub>2</sub> mainly affects the carbohydrate and lipid content suggesting that ocean acidification may change metabolic pathways of carbon in kelps (Gordillo et al., 2016). Increased CO<sub>2</sub> also affects photosynthetic acclimation under UV radiation in Arctic *A. esculenta* and *S. latissima* (Gordillo et al., 2015). Experimental observations support that interactions between temperature and CO<sub>2</sub> are low, indicating a higher resilience of Arctic kelp communities to these climate drivers than their cold temperate counterparts (Olischläger et al., 2014; Gordillo et al., 2016).

### SM3.2.7 Southern Ocean Foodwebs

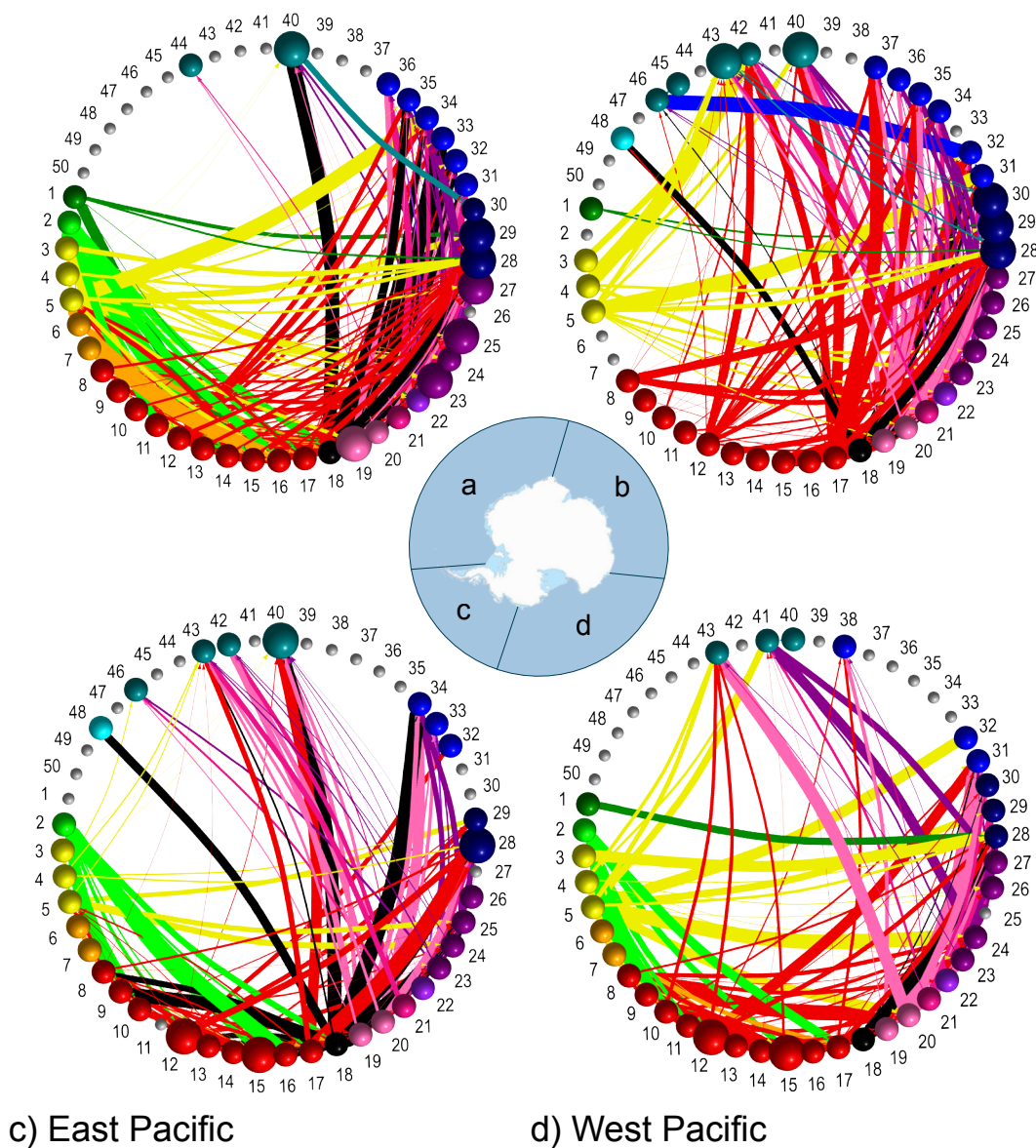
Marine foodwebs encompass the relationship between predators and prey in the oceans, also reflecting the interactions between the environment, primary production and the transfer of energy through ecosystems. Southern Ocean foodwebs are complex and while Antarctic krill (*Euphausia superba*) play a central role as grazers and as prey items for fish, squid, marine mammals and seabirds, the trophic role of this species varies between different regions (Section 3.2.3.2; Figures SM3.6 and SM3.7). No information is currently available regarding projected changes in the configuration of Southern Ocean foodwebs at the circumpolar or sector scale.



**Figure SM3.6** | Configuration of the Southern Ocean foodweb (updated from McCormack et al., 2017). Foodweb groups are coloured according to broad taxonomic groups (e.g., yellow for benthic organisms, red for zooplankton) with numbers corresponding to the name of the group listed in the key. Silhouettes are representative of the types of organisms associated with each group. Connections are coloured according to prey species/group and are directed towards the relevant predator group.

## a) Atlantic

## b) Indian



**Figure SM3.7** | Configurations of foodwebs in the four major oceanic sectors of the Southern Ocean (sector boundaries represented in central Antarctic map) **a)** The Atlantic Sector **b)** Indian Sector **c)** East Pacific Sector **d)** West Pacific Sector (updated from McCormack et al., 2017). Colours and numbers correspond to those listed within the key. The size of different nodes (groups) is indicative of the number of species aggregated within each group and the width of the connections corresponds to the average fraction of occurrence of the trophic interaction between the two groups as reported in the Scientific Committee on Antarctic Research (SCAR) Southern Ocean Diet and Energetics Database. Grey nodes indicate no fraction of occurrence data is currently available for the associated group in the database with other nodes coloured according to broad taxonomic groups (e.g., yellow for benthic organisms, red for zooplankton). Connections are coloured according to prey species/group and are directed towards the relevant predator group.



### SM3.3 Polar Ice Sheets and Glaciers: Changes, Consequences and Impacts

#### SM3.3.1 Methods of Observing Ice Sheet Changes

Since the late 20th century and the beginning of the satellite era, frequent observations of ice sheet mass change have been made using three complementary approaches: 1) volume-change measurements from laser or radar altimetry, combined with modelled estimates of the variable density and compaction of firn and snow to calculate mass change; 2) input-output budgeting, comparing modelled surface mass balance inputs over major glacier catchments to mass outputs through glacier flux gates at or near the grounding line, using surface flow velocities estimated from radar or optical satellite images and ice thickness data; 3) changes in gravitational field over the ice sheets from satellite gravimetry. Since AR5 there has been substantial improvements in high temporal and spatial resolution ice velocity mapping (e.g., Nagler et al., 2015). For the Greenland and Antarctic ice sheets, pre-satellite mass changes have been reconstructed using firn/ice core and geological evidence. Where possible, Chapter 3 uses palaeo evidence to contextualise assessments of recent mass changes.

##### SM3.3.1.1 West Antarctica and Antarctic Peninsula

###### *Intercomparison between satellite methods over a common period*

Comparing the three satellite methods described above for the 2003–2010 period, the estimates from altimetry, gravimetry and input-output budgeting for the West Antarctic Ice Sheet (WAIS) are  $-70 \pm 8 \text{ Gt yr}^{-1}$ ,  $-101 \pm 9 \text{ Gt yr}^{-1}$  and  $-115 \pm 43 \text{ Gt yr}^{-1}$  (The IMBIE Team, 2018) or, for a combined gravimetry-altimetry assessment,  $-98 \pm 13 \text{ Gt yr}^{-1}$  (Mémin et al., 2014) (*medium evidence; high agreement* in sign, *medium agreement* in magnitude). For the Antarctic Peninsula (AP), the equivalent values are  $-10 \pm 9 \text{ Gt yr}^{-1}$ ,  $-23 \pm 5 \text{ Gt yr}^{-1}$  and  $-51 \pm 24 \text{ Gt yr}^{-1}$  (The IMBIE Team, 2018) (*medium evidence; high agreement* in sign, *medium agreement* in magnitude).

###### *West Antarctic Ice Sheet intercomparison of satellite-derived mass changes through time*

A substantial increase in WAIS mass loss reported by two multi-method studies (Bamber et al., 2018; The IMBIE Team, 2018) (Table SM3.6) is supported by additional estimates from input-output budgeting of  $-34 \pm 9 \text{ Gt yr}^{-1}$  in 1979–2003, increasing to  $-112 \pm 12 \text{ Gt yr}^{-1}$  in 2003–2016 (Rignot et al., 2019) and  $-214 \pm 51 \text{ Gt yr}^{-1}$  between approximately 2008 and 2015 (Gardner et al., 2018), by a satellite radar altimetry-derived rate of  $-134 \pm 27 \text{ Gt yr}^{-1}$  for 2010–2013 (McMillan et al., 2014), and by studies focussing on the Amundsen Sea Embayment (ASE) (below).

###### *West Antarctic Ice Sheet mass loss concentrated in the Amundsen Sea Embayment*

With *robust evidence* in the ASE, the three satellite measurement methods showed *high agreement* in both loss rates ( $-102 \pm 10 \text{ Gt yr}^{-1}$ ) and in acceleration in loss ( $-15.7 \pm 4.0 \text{ Gt yr}^{-2}$ ) for 2003–2011 (Velicogna et al., 2014). Similarly for 2003–2013 there is *high agreement* with gravimetry ( $-110 \pm 6 \text{ Gt yr}^{-1}$  with an acceleration of  $-15.1 \text{ Gt yr}^{-2}$ ) (Velicogna et al., 2014) (or a loss rate of around  $-120 \text{ Gt yr}^{-1}$  given updated observations of isostatic rebound; Barletta et al. (2018)), and with a statistical inversion of altimetry, gravimetry and Global Positioning System (GPS) data ( $-102 \pm 6 \text{ Gt yr}^{-1}$ ) (Martín-Español et al., 2016), and also with input-output budgeting ( $-138 \pm 42 \text{ Gt yr}^{-1}$ ) for 2008–2015 (Gardner et al., 2018).

###### *Antarctic Peninsula intercomparison of satellite-derived mass changes through time*

On the AP, a multi-method assessment showing an increase in mass loss from the 1990s to the last decade (Table 3.3) is supported by comparable loss estimates of  $-28 \pm 7 \text{ Gt yr}^{-1}$  for 2003–2013 from a statistical inversion of altimetry, gravimetry and GPS (Martín-Español et al., 2016),  $-31 \pm 4 \text{ Gt yr}^{-1}$  from gravimetry for 2003–2013 (with an acceleration of  $-3.2 \pm 0.6 \text{ Gt yr}^{-2}$ ) (Velicogna et al., 2014), and from radar altimetry,  $-23 \pm 18 \text{ Gt yr}^{-1}$  for 2010 to 2013 (McMillan et al., 2014) and  $-31 \pm 29 \text{ Gt yr}^{-1}$  for 2008–2015 (Gardner et al., 2018).

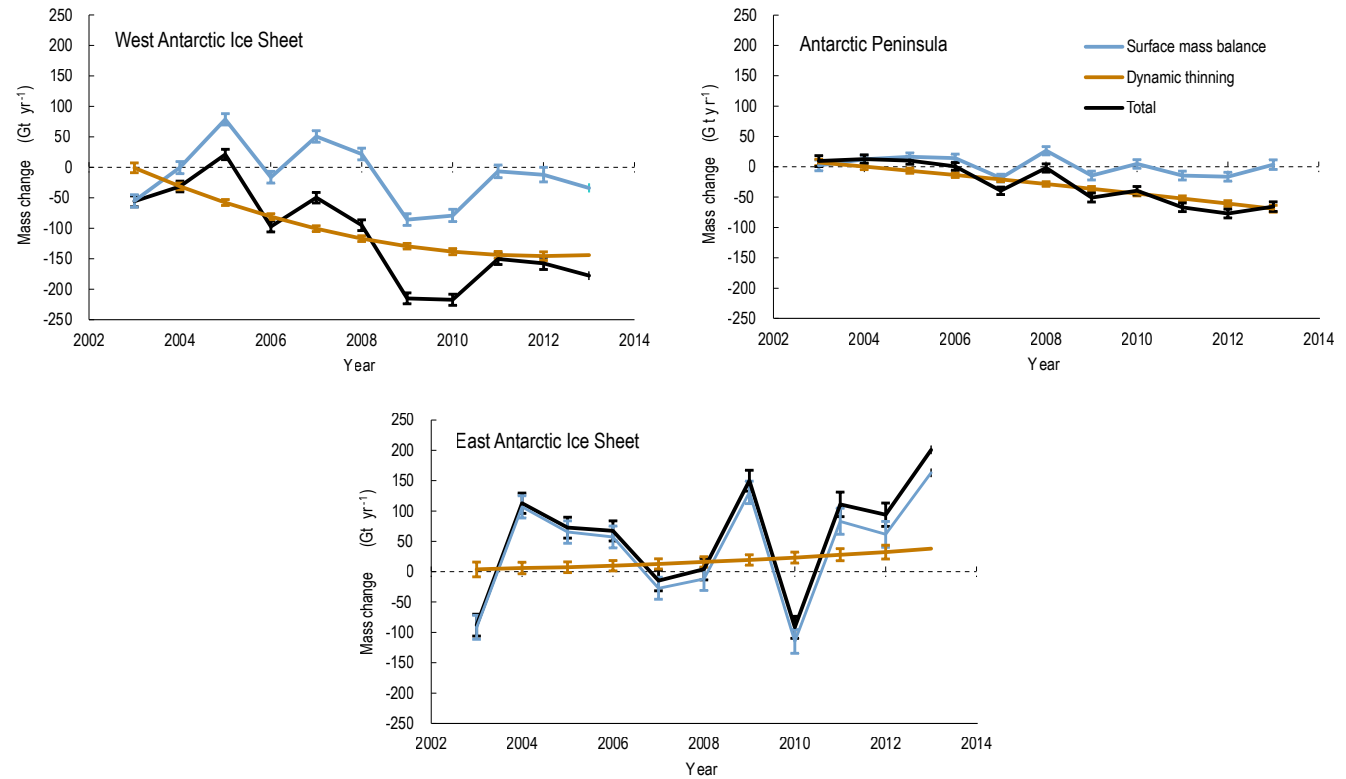
##### SM3.3.1.2 East Antarctic Ice Sheet

###### *Intercomparison between satellite methods over a common period*

Altimetry, gravimetry and input-output budgeting for the 2003–2010 period for East Antarctic Ice Sheet (EAIS) give estimates of  $+37 \pm 18 \text{ Gt yr}^{-1}$ ,  $+47 \pm 18 \text{ Gt yr}^{-1}$  and  $-35 \pm 65 \text{ Gt yr}^{-1}$  (The IMBIE Team, 2018), or, for a combined gravimetry-altimetry assessment,  $+51 \pm 22 \text{ Gt yr}^{-1}$  (Mémin et al., 2014), estimates that agree within uncertainties but vary in sign around zero.

###### *Intercomparison of satellite-derived mass changes through time*

In addition to the two multi-method satellite studies reported in Table 3.3, supporting evidence of variability but no clear multiannual trend comes from input-output budgets for EAIS ranging from  $-35$  to  $+13 \text{ Gt yr}^{-1}$  from 1979–2016 (Rignot et al., 2019) and  $+61 \pm 73 \text{ Gt yr}^{-1}$  from 2008–2015 (Gardner et al., 2018),  $-3 \pm 36 \text{ Gt yr}^{-1}$  from radar altimetry for 2010–2013 (McMillan et al., 2014), and  $+56 \pm 18 \text{ Gt yr}^{-1}$  for 2003–2013 from a statistical inversion of altimetry, gravimetry and GPS (Zammit-Mangion et al., 2014; Martín-Español et al., 2016). One altimetry study that considered observed EAIS volume changes to be dominated by ongoing post-Holocene dynamic thickening (i.e., at the density of ice as opposed to lower-density snow and firn) calculated large EAIS mass gains of approximately  $+136 \text{ Gt yr}^{-1}$  between 1992 and 2008 (Zwally et al., 2015), though this disagrees with other studies (Bamber et al., 2018) and was not reproduced in a sensitivity study that tested this assumption (Martín-Español et al., 2017).



**Figure SM3.8** | Antarctic regional mass trends for the period 2003–2013 distinguishing the surface mass balance (blue) and ice dynamics (brown) components and the total mass change (black) for the West Antarctic Ice Sheet (WAIS), Antarctic Peninsula (AP), and East Antarctic Ice Sheet (EAIS). The 1 $\sigma$  confidence interval is given by the error bars (after Martín-Español et al., 2016).

SM3.3.1.3 Greenland Ice Sheet

*Intercomparison of satellite-derived mass changes through time*

A multi-method satellite assessment (Table 3.3) (Bamber et al., 2018) is supported by similar results for overlapping periods from

radar altimetry ( $-269 \pm 51$  Gt yr<sup>-1</sup> for 2011–2016) (McMillan et al., 2016), input-output budgeting ( $-247 \pm 28$  Gt yr<sup>-1</sup> for 2000–2012) (Enderlin et al., 2014) (potentially  $-266$  Gt yr<sup>-1</sup> accounting for long-term mass gains before 1990; Colgan et al. (2015)), and gravimetry ( $-280 \pm 58$  Gt yr<sup>-1</sup> for 2003–2013) (Velicogna et al., 2014).

**Table SM3.6** | Summary of total Antarctic Ice Sheet (AIS) mass balance (combined Antarctic Peninsula (AP), West Antarctic Ice Sheet (WAIS) and East Antarctic Ice Sheet (EAIS)) for various periods.

Period	AIS Mass balance (Gt yr <sup>-1</sup> )	Uncertainty (Gt yr <sup>-1</sup> )	Source
2003–2010	–47	35	(Mémin et al., 2014)
2003–2013	–84	22	(Martín-Español et al., 2016)
2003–2013	–67	44	(Velicogna et al., 2014)
2010–2013	–160	81	(McMillan et al., 2014)
2008–2015	–183	94	(Gardner et al., 2018)
1992–2016	–93	49	(Bamber et al., 2018)
1992–2017	–109	56	(The IMBIE Team, 2018)
1992–1996	–27	106	(Bamber et al., 2018)

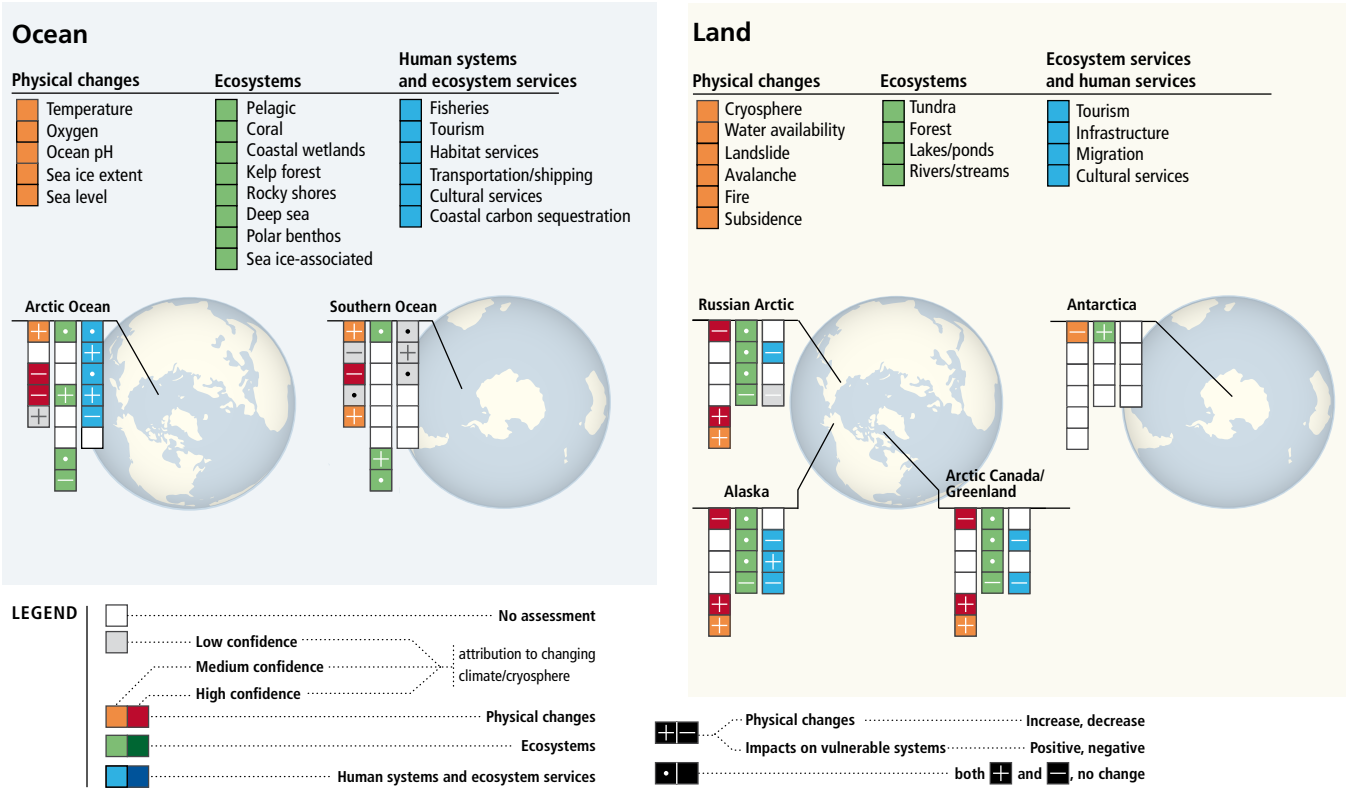
Period	AIS Mass balance (Gt yr <sup>-1</sup> )	Uncertainty (Gt yr <sup>-1</sup> )	Source
1992–1997	–49	67	(The IMBIE Team, 2018)
1997–2001	–103	157	(Bamber et al., 2018)
1997–2002	–38	64	(The IMBIE Team, 2018)
2002–2006	–25	54	(Bamber et al., 2018)
2002–2007	–73	53	(The IMBIE Team, 2018)
2007–2011	–117	28	(Bamber et al., 2018)
2007–2012	–160	50	(The IMBIE Team, 2018)
2012–2016	–191	47	(Bamber et al., 2018)
2012–2017	–219	43	(The IMBIE Team, 2018)

SM3.3.2 Projections for Polar Glaciers

**Table SM3.7 |** Region-specific projected mass changes for polar glaciers at 2100 as a percentage change relative to modelled 2015 values. Results show multi-model means and standard deviations (SD) in response to Representative Concentration Pathway (RCP) emission scenarios. Means and SD are calculated from 6 participating glacier models forced by more than 20 General Circulation Models; results for RCP2.6 are from 46 individual glacier model simulations, while the RCP8.5 results are from 88 glacier model simulations (Hock et al., 2019).

Region (see Figure 3.8)	RCP2.6 mean ± SD	RCP8.5 mean ± SD
Arctic Canada North	−12 ± 8	−23 ± 15
Arctic Canada South	−21 ± 17	−41 ± 25
Greenland periphery	−17 ± 10	−33 ± 16
Svalbard	−36 ± 24	−61 ± 23
Russian Arctic	−28 ± 22	−46 ± 29
Antarctic periphery and sub-Antarctic	−13 ± 5	−26 ± 10
All Arctic regions listed above and also including Alaska, Iceland, and Scandinavia	−21 ± 10	−38 ± 14
All polar regions (Antarctic periphery and sub-Antarctic, Arctic Canada North and South, Alaska, Greenland periphery, Iceland, Scandinavia, Svalbard, and the Russian Arctic)	−16 ± 7	−33 ± 11

SM3.4 Summary of Consequences and Impacts



**Figure SM3.9 |** Synthesis of consequences and impacts in polar regions assessed in Chapter 3. For each named region, physical changes (red/orange boxes), impacts on key ecosystems (green boxes), and impacts on human systems and ecosystem services (blue boxes) are shown. Physical changes are attributable to rising greenhouse gas concentrations and associated warming at either global or regional scales with the confidence indicated; attribution is less certain at regional scales due to higher internal variability. Physical changes in the oceans refer to bulk averages horizontally and vertically for each of the regions named. For land regions, only impacts that are at least partly attributed to a change in the cryosphere are shown, and only if assessed at medium or high confidence for the respective region. For physical changes, + or − refers to an increase or decrease in level or frequency of the measured parameter. For impacts on ecosystems, human systems and ecosystems services, + or − depicts a positive (beneficial) or negative (adverse) impacts on the relevant service, respectively. A dot represents both positive and negative impacts being observed. The physical changes in the ocean are defined as: Temperature in the 0–700 m layer of the ocean, Oxygen in the 0–1200 m layer or oxygen minimum layer, Ocean pH is surface/upper ocean pH. Ecosystems on Land: Tundra refers to Arctic tundra and the terrestrial Antarctic ecosystems. Underlying data and cross-references to sections are given in Tables SM3.8–SM3.10.



**Table SM3.8** | Observed physical changes in the ocean and cryosphere in the polar regions as depicted in Figure SPM.2 and Figure SM3.9.

Region	Location	Physical Changes	Direction of change	Notes	Detection Confidence	Attribution to climate change	Section Reference
<b>Ocean</b>							
Arctic	Ocean	Temperature	Increase	Temperature assessed in a bulk average sense over the region	High	Medium	3.2.1.2.1
Arctic	Ocean	Oxygen	N/A				
Arctic	Ocean	Ocean pH	Decrease in pH (acidification)	pH assessed at surface / upper ocean	High	High	3.2.1.2.4
Arctic	Ocean	Sea Ice Extent	Decrease		High	High	3.2.1.1
Arctic	Ocean	Sea level	Increase		Low	Low	4.2.2.6
Antarctic	Southern Ocean	Temperature	Increase	Temperature assessed in a bulk average sense over the region	High	Medium	3.2.1.2.1
Antarctic	Southern Ocean	Oxygen	Decrease		Medium	Low	5.2.3
Antarctic	Southern Ocean	Ocean pH	Decrease in pH (acidification)	pH assessed at surface / upper ocean	High	High	3.2.1.2.4
Antarctic	Southern Ocean	Sea Ice Extent	Increase and decrease		High	Low	3.2.1.1
Antarctic	Southern Ocean	Sea level	Increase		Medium	Medium	4.2.2.6
<b>Land</b>							
Arctic	Alaska	Cryosphere	Decrease		High	High	3.4.1.1; 3.4.1.2; 3.4.1.3
Arctic	Alaska	Fire	Increase		High	High	3.4.1.2.4
Arctic	Alaska	Subsidence	Increase		Medium	Medium	3.4.1.2.4
Arctic	Canadian Arctic + Greenland	Cryosphere	Decrease		High	High	3.4.1.1; 3.4.1.2; 3.4.1.3
Arctic	Canadian Arctic + Greenland	Fire	Increase		High	High	3.4.1.2.4
Arctic	Canadian Arctic + Greenland	Subsidence	Increase		Medium	Medium	3.4.1.2.4
Arctic	Russian Arctic	Cryosphere	Decrease		High	High	3.4.1.1; 3.4.1.2; 3.4.1.3
Arctic	Russian Arctic	Fire	Increase		High	High	3.4.1.2.4
Arctic	Russian Arctic	Subsidence	Increase		Medium	Medium	3.4.1.2.4
Antarctic	Entire continent	Cryosphere	Decrease		Medium	Medium	3.4.1.2

**Table SM3.9** | Observed impacts on ecosystems related to changes in the ocean and cryosphere in the polar regions as depicted in Figure SPM.2 and SM3.9.

Region	Location (where applicable)	Ecosystem	Impact Direction	Impact Types	Detection Confidence	Attribution Confidence	Section Reference
<b>Ocean</b>							
Arctic		Pelagic	Positive and negative	Mixed impacts (+ and – ) see Figure 3.5	High	Medium	Box 3.4; 3.2.3, Fig. 3.5
Arctic		Coral	No assessment	No assessment			
Arctic		Coastal Wetlands	No assessment	No assessment			
Arctic		Polar Benthos	Positive and negative	Mixed impacts (+ and – ) with motile epifaunal biomass increasing in some regions, evidence of reductions in energy export to the sea floor, and shifting biogeography	Medium	Medium	3.2.3
Arctic		Ice-associated	Negative	Reduction in areal extent of habitat for ice algae and ice-associated marine mammals, changes in the availability of prey but also increased ice algae blooms due to reductions in multi-year ice	High	Medium	3.2.3

Region	Location (where applicable)	Ecosystem	Impact Direction	Impact Types	Detection Confidence	Attribution Confidence	Section Reference
Arctic		Deep sea	No change	No observed change (but negative impacts predicted)			3.2.3
Arctic		Kelp forest	Positive	Increased light, reduced ice scouring due to fast ice retreat. Studies limited to a few regions	Medium	Medium	3.A.2.5
Arctic		Rocky shores	No assessment	No assessment			
Antarctic		Pelagic	Positive and negative	Mixed effects (+ and –) for pelagic ecosystems summarized in Figure 3.6	Medium	Medium	Fig 3.6; 3.2.3
Antarctic		Coral	No assessment	No assessment			
Antarctic	Antarctic Peninsula	Polar Benthos	Positive	Ice shelf loss and retreat of coastal glaciers created habitat for new seabed communities	Medium	Medium	3.3.3.4; Fig 3.6
Antarctic	Antarctic Peninsula	Ice-associated ecosystems	Positive and negative	Mixed effects (+ and –). Habitat shifts for Antarctic krill and penguins associated with sea ice change	Medium	Medium	Fig 3.6; 3.2.3; Box 3.4
Antarctic		Deep sea	No assessment	No observed change (but negative impacts predicted)			3.2.3
Antarctic		Kelp forest	No assessment	No assessment			
Antarctic		Rocky shores	No assessment	No assessment			
<b>Land</b>							
Arctic	Alaska	Tundra	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Alaska	Tundra	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Alaska	Tundra	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Alaska	Boreal/montane forest	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Alaska	Boreal/montane forest	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Alaska	Boreal/montane forest	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Alaska	Rivers/streams	Negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Alaska	Rivers/streams	Negative	Wildlife	Low	Low	3.4.3.2.3
Arctic	Alaska	Lakes/ponds	Positive and negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Alaska	Lakes/ponds	Positive and negative	Wildlife	Low	Low	3.4.3.2.3
Arctic	Canadian Arctic + Greenland	Tundra	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Canadian Arctic + Greenland	Tundra	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Canadian Arctic + Greenland	Tundra	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Canadian Arctic + Greenland	Boreal/montane forest	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Canadian Arctic + Greenland	Boreal/montane forest	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Canadian Arctic + Greenland	Boreal/montane forest	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Canadian Arctic + Greenland	Rivers/streams	Negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Canadian Arctic + Greenland	Rivers/streams	Negative	Aquatic biota	Low	Low	3.4.3.2.3

Region	Location (where applicable)	Ecosystem	Impact Direction	Impact Types	Detection Confidence	Attribution Confidence	Section Reference
Arctic	Canadian Arctic + Greenland	Lakes/ponds	Positive and negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Canadian Arctic + Greenland	Lakes/ponds	Positive and negative	Aquatic biota	Low	Low	3.4.3.2.3
Arctic	Russian Arctic	Tundra	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Russian Arctic	Tundra	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Russian Arctic	Tundra	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Russian Arctic	Boreal/montane forest	Positive and negative	Vegetation	High	Medium	3.4.3.2.1
Arctic	Russian Arctic	Boreal/montane forest	Negative	Reindeer/caribou	High	Low	3.4.3.2.2
Arctic	Russian Arctic	Boreal/montane forest	Positive and negative	Wildlife	Medium	Low	Box 3.4; 3.4.3.2.2
Arctic	Russian Arctic	Rivers/streams	Negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Russian Arctic	Rivers/streams	Negative	Wildlife	Low	Low	3.4.3.2.3
Arctic	Russian Arctic	Lakes/ponds	Positive and negative	Habitat	Medium	Medium-Low	3.4.3.2.3
Arctic	Russian Arctic	Lakes/ponds	Positive and negative	Wildlife	Low	Low	3.4.3.2.3
Antarctic	Entire continent	Tundra	Negative	Invasiveness	High	Low	Box 3.4

**Table SM3.10** | Observed impacts on ecosystem services and human systems related to changes in the ocean and cryosphere in the polar regions as depicted in Figure SPM.2 and Figure SM3.9.

Region	Location (where applicable)	Ecosystem Services	Impact Direction	Impact Types	Detection Confidence	Attribution Confidence	Section Reference
<b>Ocean</b>							
Arctic		Fisheries	Positive and negative	Mixed effects (+ and –). Changes in catch level and distribution of catch observed in some regions	High	Medium	3.2.3, 3.4.3, 3.5
Arctic		Tourism	Positive	Increase in tourist marine and cruise tourism related to an increase in accessibility. Other factors also contribute to increase in tourism	High	Medium	3.2.4.2
Arctic		Habitat Services	Positive and negative	Mixed effects (+ and –). Decreases in sea ice and multi-year ice has both positive and negative changes in habitats important to ecosystem service delivery	High	Medium	3.5
Arctic		Transportation & Shipping	Positive	Increase in shipping activity concurrent with reductions in sea ice extent	High	Medium	3.2.4.3
Arctic		Cultural Services	Negative	Adaptation has mostly allowed continued provisioning wild foods, shelter and water, but at increased costs and hardships	Medium	Medium	3.5.2.2
Arctic		Coastal carbon sequestration	No assessment				
Antarctic	Southwest Atlantic	Fisheries	Positive and negative	Some evidence that changes in sea ice have influenced the area of operation of the krill fishery	Low	Low	3.2.4.1
Antarctic	Antarctic Peninsula	Tourism	Positive	Increase in tourist number, increase in tour operators, risks to vulnerable ecosystems	High	Low	3.2.4.2

Region	Location (where applicable)	Ecosystem Services	Impact Direction	Impact Types	Detection Confidence	Attribution Confidence	Section Reference
Antarctic		Habitat Services	Positive and negative	There has been an increase in the area of habitat protected, but both positive and negative changes in habitats important to ecosystem service delivery	Medium	Low	3.2.3
Antarctic		Transportation & Shipping	No assessment				
Antarctic		Cultural Services	No assessment				
Antarctic		Coastal carbon sequestration	No assessment				
<b>Land</b>							
	Alaska	Tourism	No assessment				
	Alaska	Infrastructure	Negative	Permafrost thaw and other climate related	High	Medium	3.4.3.3.4; 3.5.2.6
	Alaska	Cultural services	Negative	Livelihoods	High	High	3.4.3.3.1; 3.4.3.3.2; 3.5.2.1; 3.5.2.2; 3.5.2.3; 3.5.2.4
	Alaska	Cultural services	Negative	Health and well-being	Low	Low	3.4.3.3.2; 3.5.2.8
	Alaska	Migration	Positive (or neutral, see note in impact column)	Village relocation planning (ongoing processes, no implementation to date)	High	Medium	3.5.2.6
	Canadian Arctic + Greenland	Tourism	No assessment				
	Canadian Arctic + Greenland	Infrastructure	Negative	Permafrost thaw and other climate related	High	Medium	3.4.3.3.4; 3.5.2.6
	Canadian Arctic + Greenland	Cultural services	Negative	Livelihoods	High	High	3.4.3.3.1; 3.4.3.3.2; 3.5.2.1; 3.5.2.2; 3.5.2.3; 3.5.2.4
	Canadian Arctic + Greenland	Cultural services	Negative	Health and well-being	Low	Low	3.4.3.3.2; 3.5.2.8
	Canadian Arctic + Greenland	Migration	No assessment				
	Russian Arctic	Tourism	No assessment				
	Russian Arctic	Infrastructure	Negative	Permafrost thaw and other climate related	High	Medium	3.4.3.3.4; 3.5.2.6
	Russian Arctic	Cultural services	Negative	Livelihoods	High	High	3.4.3.3.1; 3.4.3.3.2; 3.5.2.1; 3.5.2.2; 3.5.2.3; 3.5.2.4
	Russian Arctic	Cultural services	Negative	Health and well-being	Low	Low	3.4.3.3.2; 3.5.2.8
	Russian Arctic	Migration	No assessment				

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