Review

Emerging evidence of abrupt changes in the Antarctic environment

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Human-caused climate change worsens with every increment of additional warming, although some impacts can develop abruptly. The potential for abrupt changes is far less understood in the Antarctic compared with the Arctic, but evidence is emerging for rapid, interacting and sometimes self-perpetuating changes in the Antarctic environment. A regime shift has reduced Antarctic sea-ice extent far below its natural variability of past centuries, and in some respects is more abrupt, non-linear and potentially irreversible than Arctic sea-ice loss. A marked slowdown in Antarctic Overturning Circulation is expected to intensify this century and may be faster than the anticipated Atlantic Meridional Overturning Circulation slowdown. The tipping point for unstoppable ice loss from the West Antarctic Ice Sheet could be exceeded even under best-case CO_2 emission reduction pathways, potentially initiating global tipping cascades. Regime shifts are occurring in Antarctic and Southern Ocean biological systems through habitat transformation or exceedance of physiological thresholds, and compounding breeding failures are increasing extinction risk. Amplifying feedbacks are common between these abrupt changes in the Antarctic environment, and stabilizing Earth's climate with minimal overshoot of 1.5 °C will be imperative alongside global adaptation measures to minimise and prepare for the far-reaching impacts of Antarctic and Southern Ocean abrupt changes.

Human-caused climate warming has the potential to result in abrupt and sometimes unanticipated impacts on physical and natural systems, which develop substantially faster than changes in their recent history. Abrupt, large and persistent changes can be described as regime shifts, where a system undergoes a critical transition to move to a quantifiably different state[1–3]. Regime shifts may be difficult to reverse owing to self-amplifying feedbacks, including ongoing committed changes even after climate stabilization is achieved, posing challenges to adaptive capacities of natural and human systems[3,4]. In some cases, regime shifts describe substantial, widespread, frequently abrupt and often irreversible impacts when tipping-point thresholds are exceeded in large-scale (>1,000 km) parts of the Earth system[1,5]; however, regime shifts also more broadly encompass abrupt physical and natural changes that do not fall within the tipping point definition. Recently, the usefulness of the tipping points framework has been questioned owing to its oversimplification of abrupt change dynamics across different systems, and its inefficacy in fostering meaningful climate action[6].

In this Review, we use an abrupt change framework, focusing on evidence for the system behaviours that are indicative of emerging regime shifts and tipping dynamics in the Antarctic environment. The rapidly

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growing body of scientific evidence from Antarctica and the Southern Ocean indicates that some elements of the Antarctic environment are probably more vulnerable to abrupt, self-amplifying and potentially irreversible changes in a warming climate than their more extensively studied Northern Hemisphere equivalents. We review advances that have been made since the sixth assessment cycle of the Intergovernmental Panel on Climate Change[7–10], drawing together multiple lines of evidence, including recently observed changes, process understanding, pre-observational reconstructions and future simulations. We focus on Antarctic sea ice, Antarctic Overturning Circulation, Antarctic ice sheets and ice shelves, and Antarctic and Southern Ocean biology (Extended Data Fig. 1), demonstrating the interacting and globally significant abrupt changes that are emerging in the Antarctic environment.

Antarctic sea ice

The amount of sea ice surrounding Antarctica has declined precipitously over the past decade (Fig. 1). Abrupt sea-ice loss around Antarctica developed following a small but statistically significant increase from the start of satellite observations in 1978 to the satellite era peak in Antarctic sea-ice extent in 2014[11]. This increase was attributed to enhanced sea-ice formation due to surface ocean freshening[12], and by northward wind-drift caused by strengthening westerly winds[13,14] including due to spring/summer ozone depletion that has recently stabilized owing to the success of the Montreal Protocol[15]. The increase in Antarctic sea ice up to 2014 was also characterized by strong regional compensation where areas of expansive sea ice, to some degree, balanced concurrent areas of reduced sea ice[16]. Since 2014, there has been a median poleward contraction of the sea-ice edge around Antarctica by around 120 km (Fig. 1b). In 2023, the interquartile range of sea-ice extent anomalies around the Antarctic continent spanned from −174 km (southward) to +17 km (northward) of the 1981–2010 monthly median. This wide distribution demonstrates that regional variability remains an important characteristic of Antarctic sea ice, but this regional variability has been occurring in a declining mean state over the past decade. The Antarctic average monthly sea-ice extent has frequently been more than 2 standard deviations (2σ) below the 1981–2010 mean since 2017[17], and frequently more than 3σ below since 2023 (Fig. 1a). During the record-breaking low coverage of 2023, the sea-ice extent anomaly in July (Fig. 1c) reached more than 7σ below the 1981–2010 daily climatology[18]. The remarkable loss of Antarctic sea ice over the past decade suggests that either a regime shift to a new sea-ice state is underway[19,20], or that the satellite record is insufficient to fully characterize the natural range of sea-ice variability[18].

Sea-ice reconstructions spanning the past century or more demonstrate that recent ice loss is exceptional in the context of natural variability (Fig. 1d and Extended Data Fig. 2). A seasonally resolved 1905–2020 reconstruction[21] of Antarctic sea-ice extent lies almost entirely within the $\pm 3\sigma$ range of observed 1981–2010 variability (Fig. 1d and Methods). By contrast, the observed winter (June–August) mean anomalies of 2023 fell below -6σ, far exceeding reconstructed twentieth century variability. The observed annual sea-ice extent anomaly in 2023 was also below -6σ based on 1981–2010 variability, and far beyond the range of reconstructed Antarctic sea-ice variability over the past three centuries[22] (Extended Data Fig. 2a). Together, the independent long-term perspectives of multiple reconstructions[21–24] (Fig. 1d and Extended Data Fig. 2) demonstrate that the exceptional recent loss of Antarctic sea ice has moved this system far below its range of expected natural variability.

Recent Antarctic sea-ice loss may represent an intensification of the long-term decline that occurred through the twentieth century. This decline is replicated through observation-based statistical[21] (Fig. 1d) and Bayesian reconstructions[24,25] (Extended Data Fig. 2b); model assimilation reconstructions informed by observations[23] and palaeoclimate proxy networks[22] (Extended Data Fig. 2a); and regional process-based reconstructions from multiple sources (Extended Data Fig. 3). In the satellite record of Antarctic sea ice, the long-term declining trend is obfuscated by the 2007–2016 anomalously high sea-ice state[19] and possibly also by unusually low sea-ice extent in the late 1970s when satellite observations began[23,24]. The rapid transition to a low sea-ice state around 2016[19] brought Antarctic sea ice in line with a continuation of the twentieth century linear trend, consistent with the superposition of a long-term decline and decadal variability[26] (Fig. 1d and Extended Data Fig. 2), but the decline in 2023 was far more extreme and may indicate an acceleration of Antarctic sea-ice loss.

Multiple early warning indicators[27,28] point to the recent Antarctic sea-ice decline being part of a system regime shift. First, variability in Antarctic sea-ice extent has increased since 2007[19], with summer sea-ice variability doubling from 2007–2023 compared with 1979–2006 and suggesting that sea ice is approaching a critical transition[20]. The longer-term perspective from sea-ice reconstructions confirms that the recent increase in monthly, seasonal and annual variability of Antarctic sea ice is exceptional in the context of natural variability during the past several centuries (Fig. 1e and Extended Data Fig. 2). Increased persistence (autocorrelation) of Antarctic summer sea-ice area is a second indicator that this system is losing resilience to recover from perturbations as it approaches an abrupt critical transition[20], and reconstructions strengthen evidence that the recent increase in persistence represents a structural change in the sea-ice system[24]. Increased coherence in sea-ice anomalies between regions is a third early warning indicator of a regime shift underway in Antarctic sea ice[16,20], and the recently observed increased regional coherence is unusual in the long-term context of reconstructed regional sea-ice variability (Extended Data Fig. 4). This change in regional behaviour may reflect the importance of widespread ocean warming on recent, persistent Antarctic sea-ice declines[14,19,20,29,30] compared to the atmospheric processes that dominated regional variability during the twentieth century[11,13,14] (Extended Data Fig. 4). Since 2016, thinning of Antarctic winter sea ice has resulted in earlier retreat that has increased ocean surface warming and delayed the formation and thickening of sea ice the following winter[31]. This self-perpetuating process strengthens evidence connecting recent Antarctic sea-ice loss with ocean warming[19,29] and supports statistical evidence of a regime shift in Antarctic sea ice.

Antarctic sea-ice loss over the past decade has rivalled Arctic sea-ice declines (Fig. 2 and Extended Data Fig. 5), and may also have a greater potential for irreversibility (Extended Data Figs. 6 and 7). The abrupt decline in the Antarctic winter sea-ice maximum since 2014 has been 4.4 times faster than the decline in the Arctic sea-ice maximum since 1979 (Fig. 2a and Extended Data Fig. 5). In effect, this means that Antarctic winter sea-ice loss over the past decade is of similar magnitude to the total Arctic winter sea-ice loss over the past 46 years. Similarly, the decline in the Antarctic summer sea-ice minimum since 2014 has been 1.9 times faster than the summer sea-ice decline in the Arctic over the past 46 years (Fig. 2b and Extended Data Fig. 5). The more rapid recent decline in Antarctic summer sea ice, combined with the fact that there is climatologically less summer sea ice around Antarctica compared with the Arctic, means that if current trends were to continue Antarctica could become essentially sea-ice-free in summer sooner than the Arctic (Fig. 2b). Arctic sea-ice loss has frequently been included in global tipping-point syntheses[5,32], but is assessed to not be a tipping element owing to its linear response to global temperature change and potential reversibility in climate recovery scenarios[9] (Fig. 2 and Extended Data Fig. 6). By contrast, multi-century commitments to Southern Ocean warming[33] mean that even after climate stabilization is achieved it is possible that Antarctic sea ice will continue to decline and ice-free summers will become more prevalent[34] (Extended Data Fig. 7), though this important finding requires verification across other Earth system models[35,36]. Climate assessments have placed low confidence on simulated future changes in Antarctic sea ice owing to the divergence

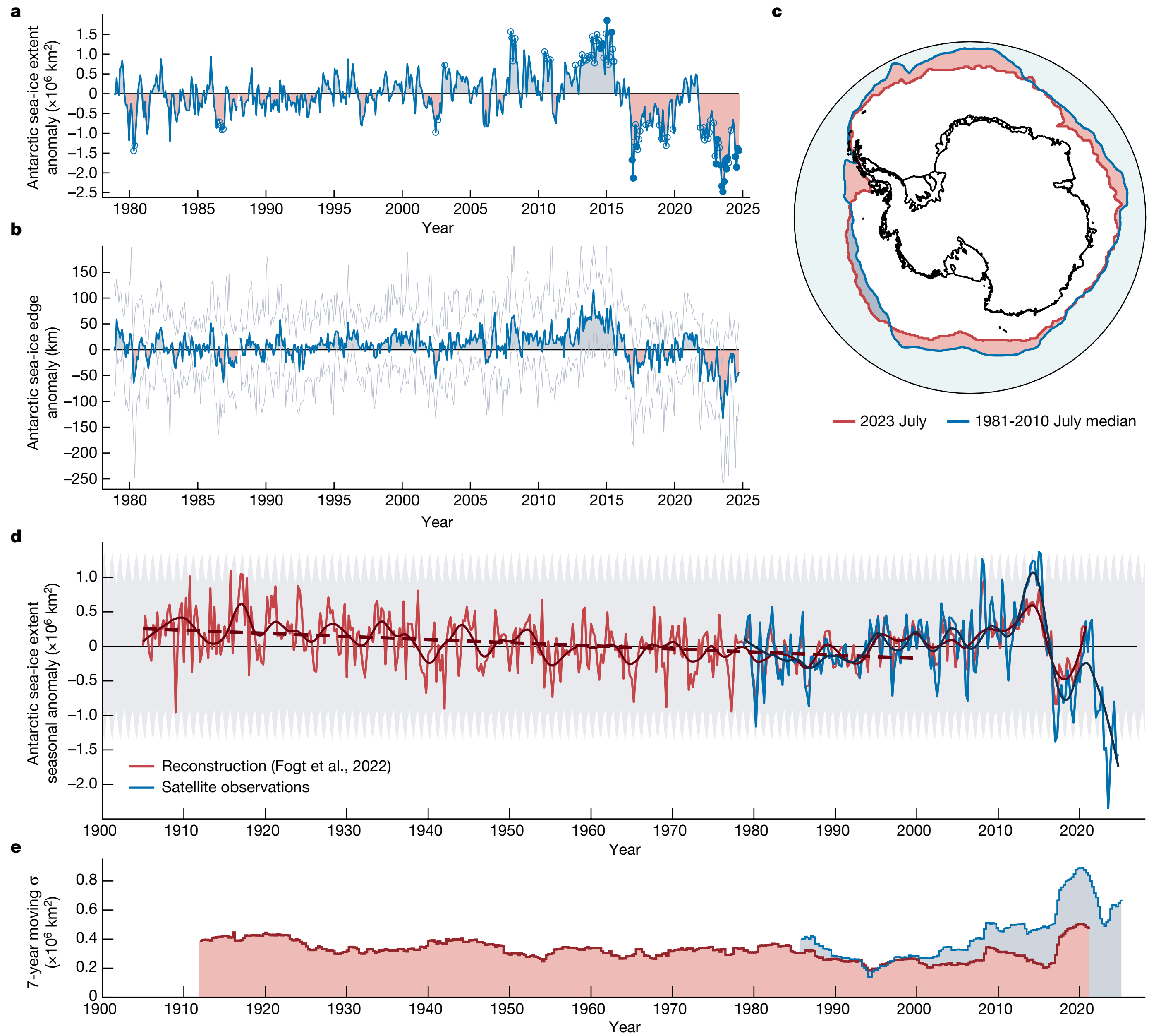

Fig. 1 | Context of the recent Antarctic sea-ice decline. a, Antarctic sea-ice extent anomalies in satellite observations relative to 1981–2010 monthly mean climatology. Open circles indicate monthly anomalies in excess of $\pm 2\sigma$ and filled circles indicate those in excess of $\pm 3\sigma$. **b**, Median (blue line) monthly anomalies and interquartile range (grey lines) in the sea-ice edge compiled for the maximum northerly extent in 2° longitudinal sectors around Antarctica, calculated relative to 1981–2010 monthly median. In 2023 the median sea-ice edge around Antarctica had contracted 61 km southward relative to 1981–2010 conditions, and the sea-ice edge distribution was significantly different ($P < 0.01$; Wilcoxon rank sum test) from any previous year since satellite observations began. **c**, Map showing sea-ice extent for July 2023 (red line) relative to 1981–2010 July median (blue line). Red (grey) shading shows regions where the sea-ice edge in July 2023 was farther South (North) than the 1981–2010 median. **d**, Historical context of Antarctic sea-ice extent seasonal anomalies from an observation-based reconstruction[21] (red; Methods), shown alongside satellite-derived sea-ice extent (blue). Thick, dark curves show 7-year LOESS filters of the seasonal data, and dashed red line shows the reconstructed twentieth century linear trend (0.43 ± 0.06 million km² decline from 1905 to 1999). Datasets plotted relative to their 1981–2010 mean, and grey shading shows $\pm 3\sigma$ range of observed seasonal sea-ice extent anomalies over 1981–2010. Out of the 464 seasons in the 1905–2020 'best-fit' sea-ice reconstruction (shown), only 3 exceeded the $+3\sigma$ level of observed 1981–2010 climatology, and none fell below -3σ. Across all reconstruction members[21], only 16 of the 3,480 seasons fall below -3σ (Methods). For comparison, 7 out of 8 seasons since summer 2022/23 have been below -3σ, and winter of 2023 was below -6σ. **e**, Moving seven-year standard deviation of seasonal sea-ice observations (blue) and reconstruction (red), plotted at the final season of each seven-year window.

of observations and models during the satellite era[8,9]. However, recent sea-ice loss now brings observed Antarctic sea-ice change into closer agreement with model results[37]. We propose that the overwhelming evidence of a regime shift in Antarctic sea ice will probably now see the expected human-forced decline in Antarctic sea ice dominate the internal variability of this system.

Abrupt Antarctic sea-ice loss over the past decade has shifted this system away from its natural behaviour of past centuries (Figs. 1 and 2 and Extended Data Figs. 2–5), with evidence for self-perpetuating processes as sea-ice thins and ocean heat uptake increases[31] that may be irreversible even at less than 2 °C global warming (Extended Data Fig. 7). Implications of this abrupt sea-ice loss are widespread. Sea-ice

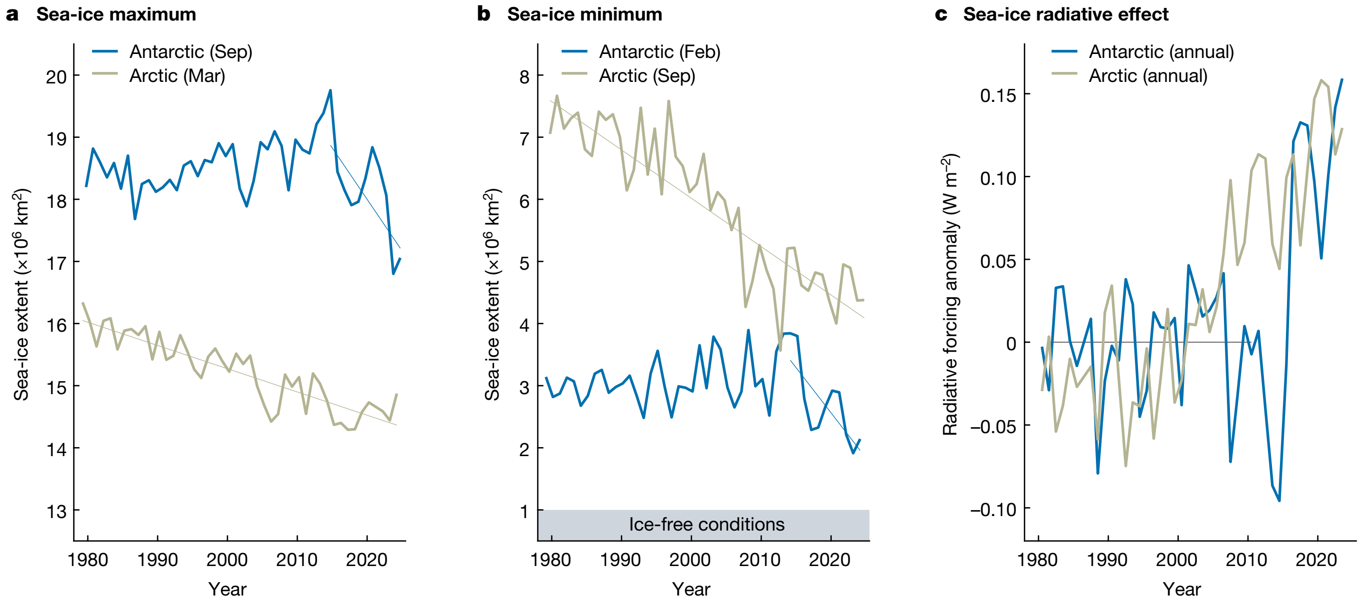

Fig. 2 | Comparison of Antarctic and Arctic sea-ice changes. a, Satellite record of annual maximum sea-ice extent for Antarctica (September) and the Arctic (March). Thin lines indicate linear trends since 2014 (Antarctica) or 1979 (Arctic). For further context, moving decadal trends are shown in Extended Data Fig. 5. **b**, As in **a** but for the annual minimum sea-ice extent in Antarctica (February) and the Arctic (September). Grey shading indicates sea-ice-free conditions (<1 million km^2), and it has been assessed that the Arctic is likely to experience an essentially ice-free summer[9] at least once before 2050. **c**, Annual radiative effect anomalies[38] associated with sea-ice change in the Arctic and Antarctic, expressed as anomalies relative to 1981–2010 means (thin horizontal line).

decline can amplify climate warming by reducing the reflectivity of high-latitude regions to incoming solar radiation[38]. Diminishing sea ice has contributed to the Arctic warming at nearly four times the global average[39]. The influence of sea-ice change as a climate amplifier depends on the albedo of the sea-ice surface, cloud cover, and the timing and latitude of sea-ice change. Antarctic sea-ice changes generally occur further equatorward than those in the Arctic owing to the differing polar geographies. As such, Antarctic sea-ice loss has the potential to cause larger changes in energy reflected from the surface. The climate warming influence (that is, positive radiative effect anomalies) of Antarctic sea-ice loss is evident following the abrupt shift to a low sea-ice state since 2016, and radiative effect anomalies generated by Antarctic sea-ice loss are now equivalent to those associated with Arctic sea-ice loss[38] (Fig. 2c). The intensity of the radiative forcing effect from Antarctic sea-ice loss now has the potential to enhance summer ocean heat uptake[40] and amplify regional warming in Antarctica and the broader Southern Hemisphere[41,42]. The current regime shift in Antarctic sea ice might also promote abrupt changes in other parts of the Antarctic and Southern Ocean system (Extended Data Fig. 1); including through its potential to reduce dense shelf water production[43,44], enhance winter ocean heat loss and Southern Ocean storminess[45], increase wave disturbances that affect ice-shelf stability[46], and trigger catastrophic tipping points for dependant species and ecosystems[47,48].

Antarctic Overturning Circulation

The global ocean meridional overturning circulation is a large-scale system of ocean currents that have a crucial role in regulating Earth's climate by transporting heat, carbon, nutrients and oxygen. Changes in meridional overturning circulation strength have driven past abrupt climate changes, and a strong overturning circulation has been key to Earth's climate stability over the past 11,000 years[49]. The global overturning circulation is often described as having two 'cells'; an upper cell sourced in the Atlantic, overlying a lower cell originating from the Southern Ocean. The Atlantic Meridional Overturning Circulation (AMOC) cell forms cold and salty dense waters in the North Atlantic that sink and circulate around the global ocean at depth. The AMOC is a well-established tipping element[1,5], and it is very likely that an AMOC slowdown will occur this century[9] and collapse is considered as likely as not by 2300[7]. The Antarctic Overturning Circulation cell involves the production of dense shelf waters around the Antarctic continental margin (Fig. 3a), which then overflow down the continental slope into the abyssal ocean as Antarctic Bottom Water[50] (Extended Data Fig. 1). Global climate models consistently project a slowing or collapse of the Antarctic Overturning Circulation under a warming climate[8,51,52] (Fig. 4b). However, confidence in these climate models to assess Antarctic Overturning Circulation change has been limited by unrealistic open ocean top-to-bottom convection that characterizes the modelled overturning[51–53]. Other limitations include uncertainties in modelled Antarctic sea-ice change[8], and the absence of interactive ice sheets or shelves and their associated meltwater inputs around the Antarctic coast[19,54,55]. These limitations have resulted in Antarctic Overturning Circulation being described as a potential but uncertain tipping element[5].

Sea-ice formation drives the production of dense shelf waters, and thus the Antarctic Overturning Circulation. When seawater freezes to form sea ice, rejection of salt causes the ocean surface water to become heavier and sink. Production of these dense shelf waters is known to occur in four areas around the Antarctic continent—the Weddell Sea, Cape Darnley/Prydz Bay, the Adélie Land Coast and the Ross Sea (Fig. 3a). Production is maintained by katabatic winds that push sea ice away from the coast, resulting in semi-permanent areas of open water (polynyas) where sea ice is formed[13] (Extended Data Fig. 1). Variations in sea-ice formation have been linked to variations in Antarctic Bottom Water production in the Ross Sea[44], and a decline in sea-ice formation has been suggested as a primary cause for an observed 30% slowdown in bottom water production in the Weddell Sea since 1992[43] (Fig. 3b). We note that the recent rapid decline in Antarctic sea-ice extent (Fig. 1) does not imply a reduction in sea-ice formation in all areas of dense water production around coastal Antarctica. This is because sea-ice extent is related to ice formation, transport and break-up[56] and the main regions of observed sea-ice loss are at the northern boundary of the sea-ice zone, far from dense water production regions.

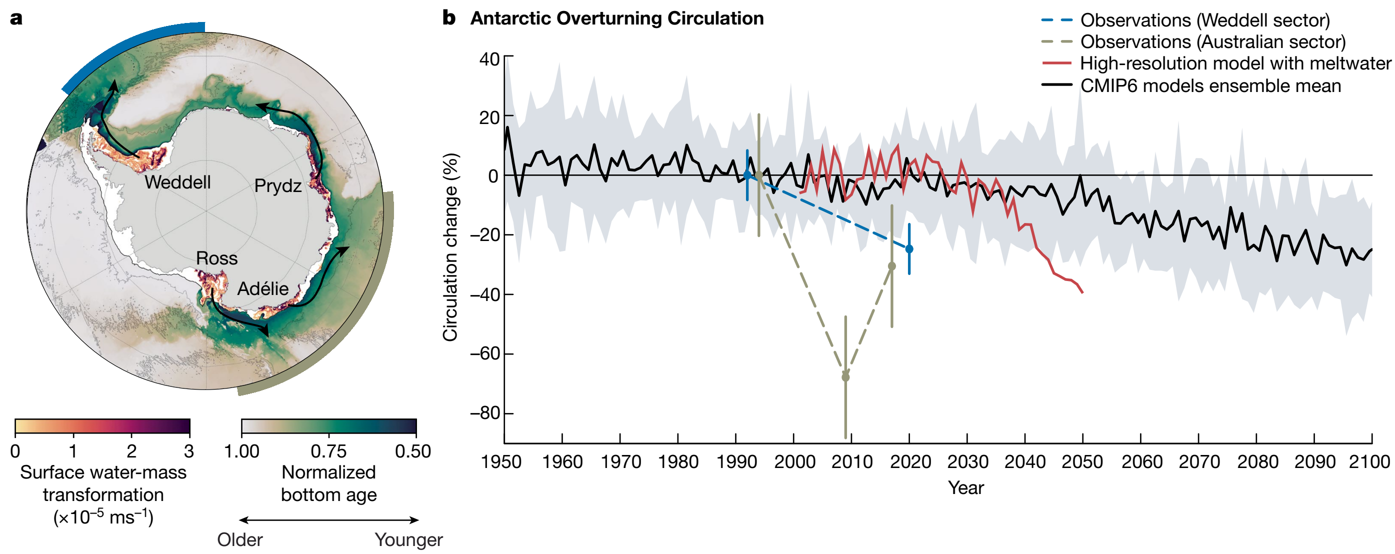

Fig. 3 | Observed and modelled changes in Antarctic Overturning Circulation. **a**, Bottom water formation regions around the Antarctic coast (red shading) are accurately captured in a high-resolution (0.1°) ocean–sea ice model (ACCESS-OM2-01)[191]. Arcs denote the longitude range of observations from the Australian Antarctic Basin sector (green) and the Weddell sector (blue) that are shown in **b**. Panel **a** adapted with permission from Ruth Moorman. **b**, Changes in Antarctic Overturning Circulation are shown for observations from the Weddell sector since 1992[43] (blue) and the Australian–Antarctic Basin sector since 1994[58] (green), as well as the circum-Antarctic CMIP6 multi-model mean across 18 models expressed as the change in the abyssal cell strength relative to the 1981–2010 baseline (black, with ±1σ model spread in grey), and the ACCESS-OM2-01 model (as in **a**) forced with anthropogenic forcings and Antarctic meltwater expressed as the change in abyssal cell strength relative to the control run[55] (red) (Methods).

Melting of ice sheets and ice shelves adds freshwater to the coastal ocean around Antarctica and is another mechanism with potential to generate an abrupt decline in Antarctic Overturning Circulation. Melting of ice shelves and calving of icebergs in West Antarctica has resulted in sustained ocean freshening in the Ross Sea since the 1950s[57]. This is thought to have caused the 30% decline in Antarctic Bottom Water transport in the Australian Antarctic Basin (downstream of the Ross Sea production region) observed since 1994[58] (Fig. 3b). Accelerating ice loss from West Antarctica could cause cessation of Ross Sea dense shelf water production by mid-century[57]. This vulnerability is supported by interannual-forced simulations of a high-resolution model that accurately simulates dense shelf water production around coastal Antarctica, which suggest production can cease altogether during mild winters[59]. In this same model, the addition of meltwater to the surface ocean drives a projected 42% decline in Antarctic Bottom Water formation by 2050 in a high-warming scenario[55] (Fig. 3b). Similarly, high meltwater forcing in a coarser resolution ocean model generates a near complete shutdown of Antarctic Bottom Water production this century[54]. This evidence suggests that a rapid and substantial slowdown in Antarctic Overturning Circulation is already underway, with observations suggesting that modelled rates of future decline may be underestimated[55,58] (Fig. 3b).

Palaeoclimate evidence identifies that the Antarctic Overturning Circulation has undergone substantial changes over centennial, millennial and glacial–interglacial timescales. Multiple factors influence dense shelf water production around Antarctica, and thus the palaeoclimate response is not uniformly related to global temperature changes. During glacial periods, cooler conditions and expanded Antarctic sea ice resulted in Antarctic Bottom Water that was colder and much saltier than today[60,61]. This very dense water expanded to fill more of the global ocean owing to reductions in North Atlantic Deep Water formation[60,61], and was also more sluggish, resulting in older[62], less-ventilated[63] and more CO_2-rich[64] bottom waters. In the Weddell Sea, there is evidence of abrupt transitions where dense water production ceased during the last two glaciations owing to expansion of the Antarctic Ice Sheet across the Weddell Shelf production region[65]. During the Last Deglaciation, a pronounced episode of Antarctic Ice Sheet retreat contributed to a rapid sea-level rise event known as Meltwater Pulse 1A[66]. Modelling suggests the addition of freshwater from ice-sheet loss during this event significantly reduced[67] or shutdown[68] Antarctic Bottom Water formation. In past interglacials, when temperatures were as warm or warmer than today and the Antarctic Ice Sheet was less extensive[69,70], marine sediments indicate abrupt stagnation of Antarctic Overturning Circulation lasting several thousand years[65,71,72]. During the Last Interglacial this is thought to have been caused by coastal freshening due to Antarctic Ice Sheet melting and retreat[71,73]. Modelling studies further suggest that reduced sea-ice formation during warm conditions of the Last Interglacial contributed to the weakened Antarctic Overturning Circulation at this time[74]. Palaeoclimate evidence thus increasingly points to the potential for abrupt transitions in Antarctic Overturning Circulation, with differing processes dominating in different climate states. Evidence for slowdown or stagnation of Antarctic Overturning Circulation related to reduced sea-ice extent and enhanced freshwater inputs from ice-sheet loss during rapidly warming past climates is of particular concern given recent and projected changes in Antarctica.

Advances in observations, process-based understanding, modelling and palaeoclimate evidence, suggest the Antarctic Overturning Circulation is already undergoing rapid change at current warming levels and will continue to decline in the 21st century. This decline may be even more abrupt than the equivalent Northern Hemisphere processes, with one study indicating the decline in Antarctic Bottom Water transport by 2050 could be more than double the decline in AMOC strength[55]. This rapid decline in Antarctic Overturning Circulation may be related to the close proximity of Antarctica's ice shelves and marine-grounded parts of the Antarctic Ice Sheet to dense shelf water production regions. A decrease in Antarctic Bottom Water production increases the temperature and transport of warm Circumpolar Deep Water onto the Antarctic continental shelf[55,75]. This is the dominant process driving observed basal ice-shelf melt in the Amundsen Sea sector and Wilkes Land[76–79], and this process may now be developing along other parts of the East Antarctic margin[80]. This ocean-ice interaction is accelerating meltwater input to the coastal ocean and increasing ocean stratification, further inhibiting Antarctic Bottom Water production. During the Last Deglaciation, the positive feedback

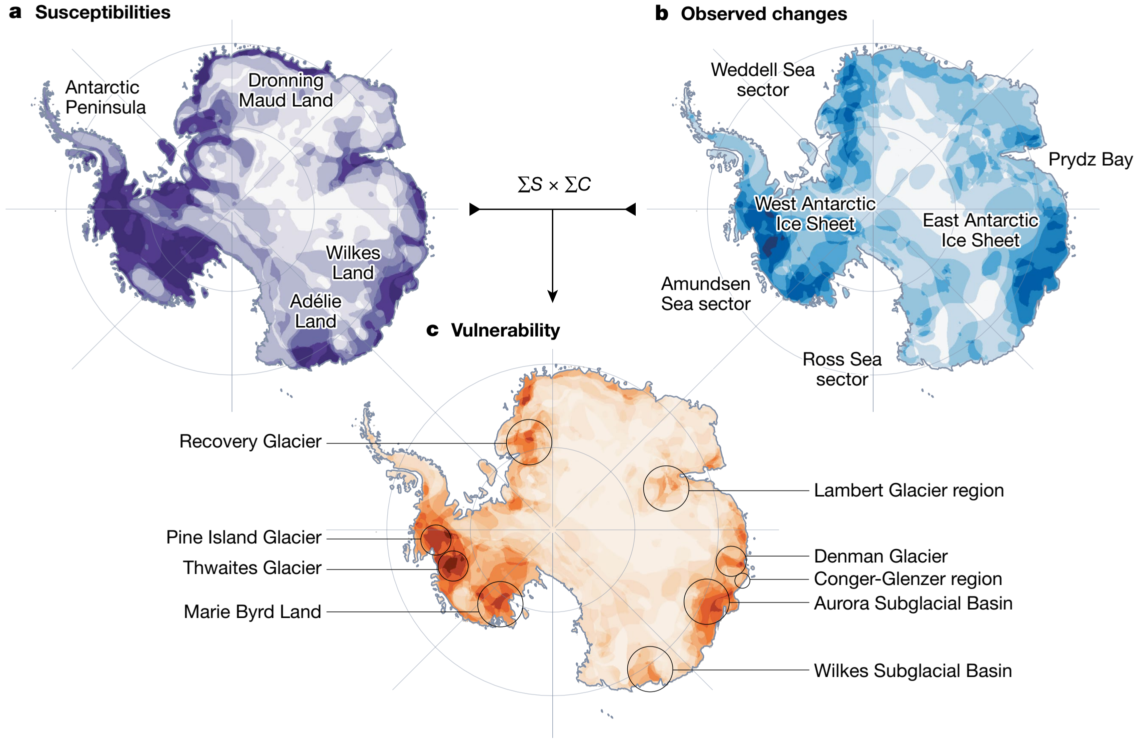

Fig. 4 | Indicative maps delineating Antarctic ice-sheet regions that may be vulnerable to abrupt change. **a**, Regions with properties that promote susceptibility of the ice sheet (purple). **b**, Regions currently undergoing observable changes in ice sheets (blue). **c**, The product of these two maps (orange) accentuates areas where ongoing changes combined with pre-existing susceptibilities are likely to generate the least stable regions of the ice sheet by enabling positive feedbacks that make the ice sheet vulnerable to rapid destabilization and tipping behaviour. The fields underlying the mapped susceptibilities and observed changes are detailed in Extended Data Fig. 8.

between Antarctic Overturning Circulation and Antarctic Ice Sheet stability caused episodes of rapid ice loss that contributed to Meltwater Pulse 1A[68]. Increases in ice-shelf melt in the Amundsen Sea region are already unavoidable this century under all future emission scenarios owing to subsurface warming driven by changes in ocean circulation[79], and regime shifts to warm-water conditions are possible under most Antarctic ice shelves in high-warming scenarios[81].

Slowdown or collapse of the Antarctic Overturning Circulation would lead to widespread climate and ecosystem impacts. The slowdown may already have had direct, observable impacts on warming[55] and deoxygenation[58] of the deep Southern Ocean. Antarctic Overturning Circulation is a critical component of the global carbon cycle that amplified global climate changes over past glacial–interglacial cycles by altering the amount of CO_2 stored in ocean and atmosphere reservoirs[64,82]. Today, the complex interplay between outgassing of old carbon in upwelling deep water, and absorption and biologically mediated storage of carbon within newly formed bottom waters, results in a net drawdown of CO_2 from the atmosphere into the Southern Ocean[83]. However, as the overturning circulation slows this balance may shift, reducing the Southern Ocean's ability to sequester anthropogenic CO_2 and generating an amplifying feedback that intensifies climate warming over multiple centuries[84]. Other far-reaching consequences of Antarctic Overturning Circulation slowdown arise through the associated increased transport of Circumpolar Deep Water onto the Antarctic continental shelf, driving ice-shelf and ice-sheet loss with global consequences for sea-level rise. Increasing meltwater in the surface ocean around Antarctica also impacts global climate; most notably by delaying (on the order of a decade or so) the exceedance of the 2 °C warming threshold specified in the Paris Agreement[75,85,86], and by causing enhanced drying over Southern Hemisphere continents, a northward shift of the Intertropical Convergence Zone, and reduced drying of the Northern Hemisphere[19,75].

Antarctic ice sheets and ice shelves

It is well recognized that the Antarctic Ice Sheet is prone to tipping dynamics[1,5]. The most vulnerable region is the West Antarctic Ice Sheet (WAIS; Fig. 4). A critical threshold for WAIS collapse is estimated around 2 °C global warming above pre-industrial temperatures[87], and a partial collapse could occur for lower temperatures[5]. Tipping dynamics in the WAIS are primarily driven by the marine ice-sheet instability (MISI), where ocean-driven melting and loss of ice-shelf buttressing in marine basins (areas with bed topography below current sea level) initiate a positive feedback between irreversible grounding-line retreat and ice loss[88–91]. Marine basins in the East Antarctic Ice Sheet are also susceptible to tipping dynamics[5], although substantial ice loss from these regions might be avoided[87,92] if global warming is limited to below 2 °C. Tipping behaviour in the non-marine basins of East Antarctica would require the surface melt–elevation feedback to be triggered, and is not expected to be initiated below 5 °C of global warming[5,87].

The Last Interglacial provides valuable constraints for abrupt Antarctic ice-sheet behaviours under sustained warming similar to present day conditions. Indirect evidence suggests that sectors of Antarctica experienced large-scale retreat under global surface temperatures ~1 °C warmer than pre-industrial conditions, contributing to global sea levels 6 metres or more above present[93]. Recent sea-level estimates are smaller[94], but still imply Antarctic ice loss contributions[73]. Octopus DNA suggests that an open seaway existed through the West Antarctic interior during the Last Interglacial[95], consistent with WAIS collapse, although ice-core sea-salt levels indicate the Ronne Ice Shelf remained largely intact and collapse was confined to the Amundsen sector[96]. The ice-sheet margin in Wilkes Subglacial Basin (Fig. 4) is also thought to have retreated during parts of the Last Interglacial[97]. Proxy-informed simulations indicate the combined effects of Last Interglacial ice-sheet elevation lowering and meltwater inputs caused strongly non-linear subsurface warming around the Antarctic margin that could have reinforced ice-shelf and ice-sheet loss[98]. These combined effects allow palaeoclimate evidence to be better reconciled with past sea-level estimates without invoking ice-cliff failure processes[98,99].

Since the 1990s, mass loss from the Antarctic Ice Sheet has increased almost sixfold[100], with major losses concentrated in marine basins[100–103]. Ice loss is attributed to increased ocean heat available in ice-shelf cavities, driving ice-shelf thinning and calving[78,79], and consequent dynamic ice loss[104–107]. Several studies have hypothesized that MISI is already underway in some West Antarctic basins[108–112]. Interdecadal climate variability may account for a recent slowdown in grounding-line retreat in the Amundsen sector[113], demonstrating the importance of regional climate factors in short-term predictability of ice-sheet change. Current WAIS grounding-line retreat might be reversible if subsurface ocean warming is not sustained[114], although this is unlikely[79] and irreversible retreat of the WAIS could be initiated on multi-centennial timescales (and unfold over millennia) under prolonged present day climate conditions[115]. In idealised ice-sheet model experiments where all ice shelves are removed, full WAIS collapse can occur over only 500 years[116]. Ultimately, timescales of irreversible retreat, once initiated, will depend on the amount of additional warming beyond the tipping threshold[117].

Ice-shelf collapse accelerates ice-sheet loss[118], and can be caused by multiple processes. In addition to basal ice-shelf melting and thinning from ocean warming[78], surface melt caused by atmospheric warming can lead to hydrofracturing that weakens ice shelves[119,120]. Hydrofracturing is implicated in the collapse of several Antarctic Peninsula ice shelves since the 1980s[121], with consequent acceleration of upstream ice flow[122–124]. The non-linear response of surface melt to increasing temperature[125] means that melting is projected to become prevalent on ice shelves around Antarctica if global warming reaches 4 °C higher than pre-industrial temperatures, making 34% of current ice-shelf area vulnerable to hydrofracture-induced collapse[126]. However, surface meltwater on Antarctic ice shelves is underestimated in observations and models, for example, owing to the omission of saturated snow and firn (slush) processes[127]. Other important processes for ice-shelf collapse are becoming apparent. Storm-driven break-up of the Conger-Glenzer Ice Shelf[128,129] (Fig. 4) in 2022 was the first observed major ice-shelf collapse in East Antarctica, and the first collapse event Antarctic-wide where surface melt was not apparent.

Abrupt changes, including the onset of irreversible tipping behaviours in the Antarctic Ice Sheet, cannot be determined from the rate of retreat or ice loss alone. Critical thresholds in grounding-line retreat can be identified using quasi-equilibrium numerical model simulations[87] and reversibility experiments[87,114,115,130]. The onset of irreversible retreat could be anticipated using early warning indicators from critical transitions theory[27,28], as applied to Pine Island Glacier[88]. However, the theoretical basis for early warning indicators can only be meaningfully applied to systems close to equilibrium, which is not the case for the Antarctic Ice Sheet. Furthermore, early warning approaches cannot predict the timing of crossing a tipping point, only that a critical transition is approaching, and observational limitations can lead to false positives in detection[131].

Earth system models are increasingly incorporating ice-sheet components to capture coupled atmosphere-ocean-ice-earth behaviours[132,133] and improve sea-level projections. A major challenge to skilful projections is the dynamic nature of ice-sheet coupling. For example, pinning points on an ice shelf can become unanchored as the ice shelf thins, locally decoupling the ice-sheet and solid-Earth systems. This process is associated with rapid acceleration and ice loss in the Antarctic Peninsula, Amundsen sector, and Aurora Subglacial Basin over recent decades[134] (Fig. 4). Another example is the increasing susceptibility of marine ice-sheet grounding zones over time, whereby melting due to warm ocean water intrusion beneath the ice sheet leads to grounding zone widening, strengthening sensitivity of ice loss to ocean warming[135]. By contrast, solid-Earth and gravitational processes might provide a negative feedback that stabilizes currently retreating grounding lines[136], particularly in West Antarctica where low mantle viscosity could drive solid-Earth rebound on decadal timescales[137,138]. Conceptual network approaches of interacting tipping elements indicate that the WAIS can initiate global-scale tipping cascades[139] owing to its relatively low critical thresholds[140], demonstrating that improved predictability of Antarctic ice-sheet tipping behaviours is critical to improving the predictability of abrupt and potentially irreversible changes globally.

In understanding the vulnerability of Antarctica to abrupt change, both the susceptibility of the ice sheet and nature of currently observed changes must be combined (Fig. 4, Extended Data Fig. 8 and Methods). We define susceptibility in terms of ice dynamic, bed and boundary, and solid-Earth properties that enhance tendencies towards abrupt behaviours (Fig. 4a), and observed changes in terms of atmospheric forcings and ice dynamic responses (Fig. 4b). Regions of greatest vulnerability (Fig. 4c) encompass those with the largest uncertainties in simulated ice-sheet evolution to 2100[141], characterized as: marine basins; areas where active subglacial hydrology systems are present[142]; and where large heterogeneities exist in basal conditions[143]. In these regions, ice–solid Earth interactions impacted by bed topography[144,145], geothermal heat[146,147] and upper mantle viscosity[148,149] may be pivotal in determining how vulnerable regions evolve in response to a warming climate.

Antarctic and Southern Ocean biology

The impacts of sustained climate pressures are becoming clear for many Antarctic biological systems[10,150,151]. Risks of abrupt change may be deduced from observed biological regime shifts and knowledge of adaptive capacity and thresholds of the unique biology of the Antarctic region. Non-climatic stressors that may add to risks for rapid and widespread biological losses include human pressures and disease, including the current outbreak of avian influenza[152,153]. Observed or anticipated regime shifts in biological systems are described here for three key operating mechanisms: habitat transformations, reproductive failures, and exceedance of physiological thresholds.

Habitat transformation leading to abrupt biological regime shifts has been documented in Antarctic terrestrial and marine systems, with associated ‘winners’ and ‘losers’. Abrupt physical changes, including ice-shelf collapse[154] and sea-ice loss[155], have led to local regime shifts in benthic shallow marine communities where filter feeder, ascidian-dominated communities are rapidly replaced by macroalgae dominated communities[151]. This response is due to increases in light[155], changes in sedimentation[156–158] and increased disturbance from iceberg scour[151,158]. Observed transformations in benthic systems have frequently resulted in a reduction in biodiversity[155]. In terrestrial biological systems of the Antarctic Peninsula, warming has resulted in rapid and self-perpetuating greening through colonisation of previously ice-covered or bare ground by mosses, algae and flowering plants (including invasive species)[159,160]. However, actual rates of greening may have been slower than interpreted from satellite imagery[161] and highlight the need for ground-truthing changes inferred by remote monitoring. The spread of flowering plant species is expected to be further perpetuated by increasing reproductive capability of the plants themselves[162]. Antarctic browning is being observed in other regions through the declining health of moss beds due to extreme desiccation caused by reductions in moisture availability from precipitation, blowing snow or meltwater flow[160,163,164]. In East Antarctica, local habitat drying is leading to replacement of an Antarctic specialist moss with a cosmopolitan species[163], and is an example of potentially irreversible change to ecosystem structure[165].

Biological losses have potentially irreversible consequences where they result in widespread and repeated breeding failures that increase extinction risks (Fig. 5). To breed, emperor penguins rely largely on stable land-fast sea ice (known as fast ice) between March or April to January. Many regions of multi-year fast ice are now transitioning to

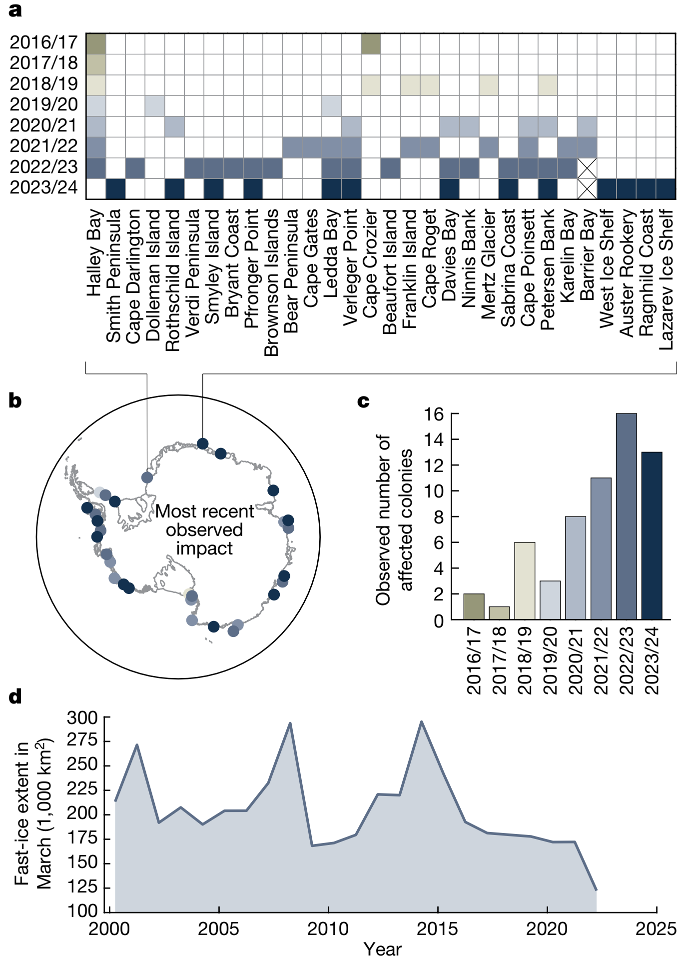

Fig. 5 | Impacts of early fast-ice breakout on emperor penguin breeding are compounding in time and space. a. Emperor penguin colonies, where increased or complete breeding failure has been inferred from satellite imagery of early fast-ice break-up since the summer of 2016–2017 (2016/17). **b**, Map showing location and most recent year of impact for the affected colonies. Data in **a** are arranged by longitude around the Antarctic continent; crosses indicate where colonies no longer exist owing to sustained open water; and year colours are applied consistently in **a**–**c**. **c**,**d**, The number of colonies affected in each year (**c**) has increased as the extent of fast ice around Antarctica has decreased (**d**), shown here for March (approximately summer minimum). The March fast-ice dataset[166] is currently only available until 2022, but fast-ice conditions have remained at historically low levels in 2023 and 2024 (A. Fraser, personal communication).

seasonal fast ice, and this shift is expected to continue[166] with potential for extinction of emperor penguins by 2100[150,167]. Since 2016, satellite imagery has documented colony-scale breeding failure events[153,168] (Fig. 5a–c). The increasing number of affected colonies includes breeding failure events that are compounding in time and space, and early fast-ice break-up before the chick fledging period is now observed in colonies around the whole Antarctic continent, independent of latitude. Of the 60+ known colonies, 30 have experienced increased or complete breeding failure events since 2016 due to early fast-ice loss, and 16 colonies have suffered two or more such events (Fig. 5a–c). In 2022, complete regional-scale breeding failure was observed for the first time in the Bellingshausen Sea[47]. In some regions, emperor penguins have moved to alternate breeding sites after habitat loss or multiple years of breeding failure[153,169]. Other species also depend on Antarctic sea ice and fast ice for breeding, including leopard, Ross and crabeater seals, krill[48] and Antarctic silverfish[170]. Sea ice is also critical for Adélie penguins during their annual moult, and sea-ice loss risks adult survival[171]. These observed impacts highlight the potential for reduced survival capacity of some Antarctic ice-dependent species (and the higher trophic predators that rely on them) under the current regime shift in Antarctic sea ice and expected ongoing future climate changes.

Southern Ocean marine species that live south of the Polar Front are adapted to extreme low temperatures and are thought to be highly susceptible to ocean warming. Diatoms are keystone phytoplankton in the Antarctic marine food web and have asymmetric thermal performance curves, with mortality occurring within a less than 2 °C window. Increases in ocean surface temperature in coming decades, including abrupt and intense marine heatwave events[172], may exceed the thermal summer maximum of many diatom species[173]. Iron stress observed in around 80% of the open Southern Ocean further exacerbates the vulnerability of diatoms by reducing their tolerance to warmer temperatures[174]. Ocean acidification is a compounding climate stressor on the physiological limits of phytoplankton and other Antarctic marine species[175,176]. Machine learning trained on historical pigment samples deconvolved satellite chlorophyll *a* changes within the seasonal sea-ice zone to identify a significant decline in diatom productivity by 18% over the past 26 years[177], whereas less-grazed phytoplankton groups have increased in abundance by 6–10%. This regime shift in Southern Ocean phytoplankton species has coincided with declines in krill, which preferentially feed on diatoms[177]. In addition to their key role in ecosystem function, Southern Ocean phytoplankton drive the export of carbon into the ocean interior and account for about 20–30% of the global ocean CO_2 drawdown[174]. Through this mechanism, exceedance of phytoplankton physiological limits has the potential for global impacts by reducing CO_2 drawdown and exacerbating human-caused climate warming.

Global context of abrupt Antarctic change

Short observations and large magnitude natural climate variability[178] have hampered the systematic assessment of abrupt Antarctic changes. The unique geographies of Antarctica and the Southern Ocean further complicate this by enabling two-time-scale processes that can delay the onset of expected human-caused climate impacts in this region[14,179–182]. Multiple aspects of human-caused climate change are now driving physical and biological changes in the Antarctic region and increasing the chances of generating regime shifts in the Antarctic environment (Fig. 6). These climate pressures include long-term increases in ocean heat, atmospheric warming, changes in atmospheric circulation, sea-level rise and ocean acidification, as well as the manifestation of these trends in extreme events. For example, collapse of the Conger-Glenzer Ice Shelf in March 2022 has been linked to an intense atmospheric river and heatwave event in East Antarctica through the associated strong winds and high swells that impacted the ice shelf[129]. Such extreme events may make abrupt changes more likely to occur (as has been argued for the Arctic)[183] by transforming slowly growing climate pressures into abrupt and potentially irreversible changes in the Antarctic environment.

There are multiple interactions between the emerging abrupt changes in Antarctica and the Southern Ocean (Fig. 6). For example, positive (amplifying) feedbacks connect destabilization of marine-grounded parts of the Antarctic Ice Sheet to the slowdown in Antarctic Overturning Circulation through meltwater forcing and subsurface ocean warming. This amplifying feedback is of critical concern as the Antarctic is characterized by large areas of marine-grounded ice and extensive ice shelves that are vulnerable to the marine ice-sheet instability and are in close proximity to areas of dense shelf water production. Some interactions within the Antarctic environment are still uncertain, including when and where the regime shift in Antarctic sea ice might alter dense shelf water production, and it is possible that the dominant process will vary by region or change over time. Overall,

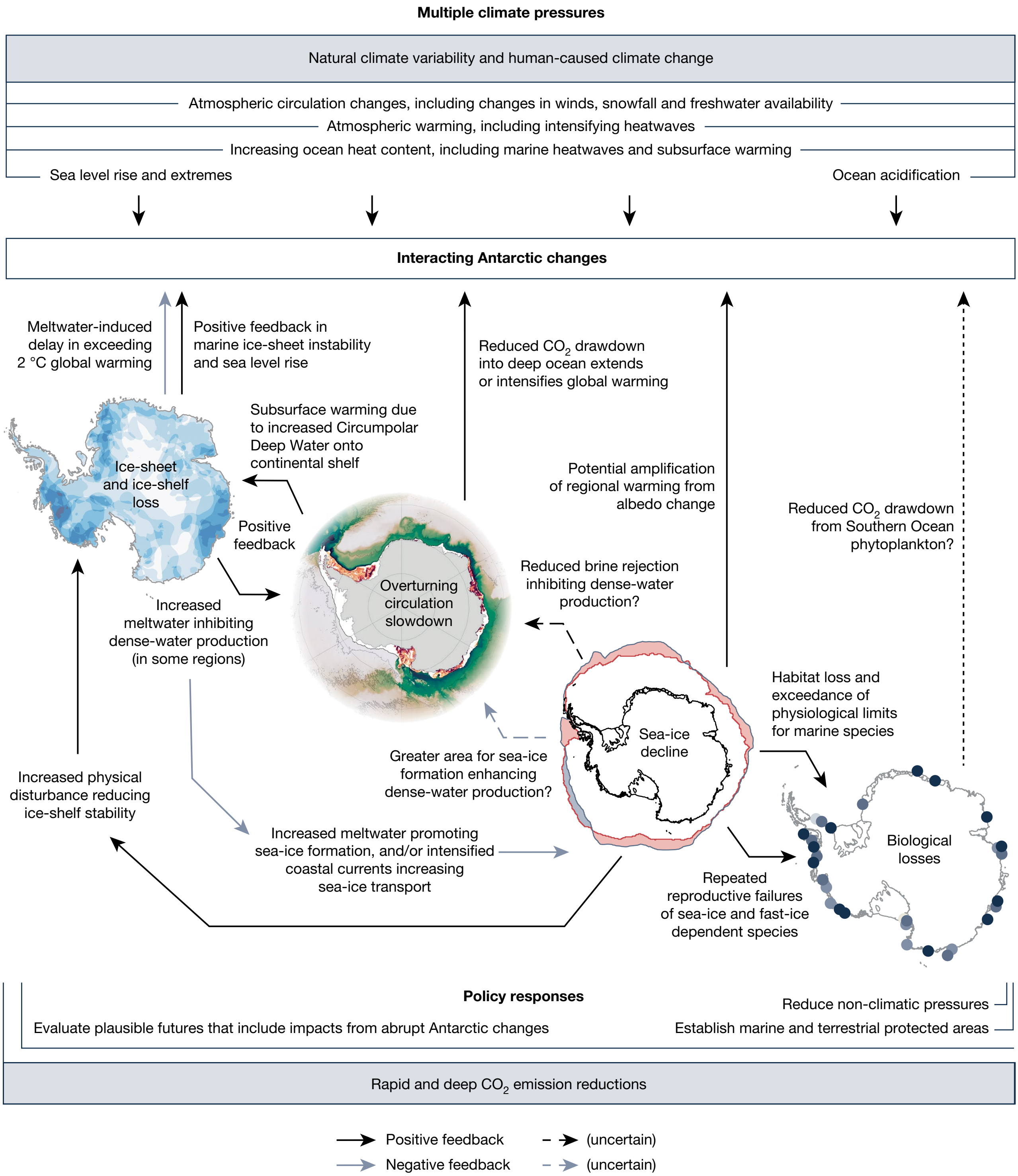

Fig. 6 | Abrupt changes in the Antarctic environment. Top, multiple climate pressures, including extreme events, are increasing the risk of abrupt changes in the Antarctic environment. Middle, there are multiple processes through which Antarctic ice, ocean and biological systems are connected to each other and feedback onto global climate drivers; most involve amplifying changes (black text and arrows), some inhibit change (grey text and arrows), whereas in some cases the dominant process connecting different elements is not yet clear (dashed arrows). Base images used to represent each Antarctic system are derived from Figs. 1 and 3–5. Bottom, policy responses to avoid abrupt Antarctic changes depend on rapid and deep CO_2 emission reductions, while other actions may aid adaptation and resilience to abrupt change in the Antarctic environment.

most anticipated interactions between different parts of the Antarctic environment are reinforcing, such that they will exacerbate changes being driven by human-caused climate changes (Fig. 6). Similarly, most of the feedbacks from Antarctic changes back onto global climate are expected to amplify human-caused climate changes (Fig. 6). Abrupt changes in the Antarctic environment are therefore expected to have global consequences, including the potential to initiate[140] and contribute to cascades of abrupt change[3,139,184].

Multiple approaches are needed to improve the predictability of abrupt and potentially irreversible changes in the Antarctic environment (Extended Data Fig. 9). Priorities for improving observations include new satellite missions, autonomous technologies and targeted field campaigns to better identify critical thresholds for species and biological systems, resolve the processes above and beneath sea ice and ice shelves, and characterize potentially vulnerable but largely unstudied regions of the Antarctic Ice Sheet. Incorporating multiple lines of evidence from pre-satellite information is critical to contextualizing the current regime shift in Antarctic sea ice, and evaluating the ability of climate models to reliably simulate Antarctic sea-ice changes. Reconstructions and modelling of ocean and ice-sheet behaviour during warm intervals of Earth's past may aid identification of vulnerable regions, the timescales over which destabilization might occur, long-term commitments expected under climate stabilization, and constrain the processes involved in abrupt changes. Recent advances have demonstrated the need for dynamically coupled ice sheets and a highly resolved coastal ocean in Earth system models to capture critical processes that will determine future abrupt change of the Antarctic ocean-cryosphere system, as well as the importance of extended, multi-model simulations to elucidate long-term commitments for Antarctic and Southern Ocean change. Improved knowledge and predictability of abrupt changes in the Antarctic environment is crucial for guiding policy that supports adaptation to, and where still possible avoids, future abrupt changes in the Antarctic region.

Avoiding abrupt changes in Antarctica and the Southern Ocean would have global benefits in limiting climate change impacts and improving prospects for successful adaptation to already unavoidable changes such as global sea-level rise[7,9]. Existing policy responses (Fig. 6) through the Antarctic Treaty System include the management of growing human impacts in Antarctica, sustainable management of Southern Ocean fisheries, and the establishment of terrestrial and marine protected areas[184–186]. These local to regional-scale policy actions may have some benefits in delaying passing critical thresholds for biological systems, but will not delay or avoid regime shifts and tipping points in the ocean-cryosphere system. Several geoengineering 'fixes' have been proposed to potentially slow warming and avoid catastrophic ice loss in Antarctica (and the Arctic), but none of these pass objective evaluations of suitability to be deployed in coming decades and many of the proposed fixes are environmentally dangerous[187]. The only assured way of reducing the risk of abrupt changes in the Antarctic environment is to make rapid and deep CO_2 emission reductions this decade, and achieve true net zero emissions this century[117,188] within a remaining global carbon budget[189] that allows for as little overshoot of 1.5 °C as possible[117]. Even if this ambitious climate change mitigation is achieved through international cooperation and national to regional-scale implementation[190], the long-term commitments for Southern Ocean warming[33] mean that climate stabilization between 1.5 °C and 2 °C may not be sufficient to avoid some abrupt and possibly irreversible changes in the Antarctic environment. This necessitates the inclusion of unknown-likelihood, high-impact outcomes[6] that account for potential impacts of abrupt Antarctic changes among the plausible futures that are used to guide adaptation responses and build resilience for the future climate impacts our world will face.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-025-09349-5.

1. Lenton, T. M. et al. *The Global Tipping Points Report 2023* (Univ. of Exeter, 2023).
This report assesses Earth system and social tipping points, aiming to inform decision-makers and the public about the risks and opportunities associated with the urgent global challenges of climate change and biodiversity loss.
2. Biggs, R., Carpenter, S. R. & Brock, W. A. Turning back from the brink: detecting an impending regime shift in time to avert it. *Proc. Natl Acad. Sci. USA* **106**, 826–831 (2009).
3. Rocha, J. C., Peterson, G., Bodin, Ö. & Levin, S. Cascading regime shifts within and across scales. *Science* **362**, 1379–1383 (2018).
4. Folke, C. et al. Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev. Ecol. Evolut. Systemat.* **35**, 557–581 (2004).
5. Armstrong McKay, D. I. et al. Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science* **377**, eabn7950 (2022).
6. Kopp, R. E. et al. 'Tipping points' confuse and can distract from urgent climate action. *Nat. Clim. Change* **15**, 29–36 (2025).
This article critiques the tipping points framework by examining the history and effectiveness of this framework, and provides recommendations for clearer and more specific descriptions of abrupt changes to better inform decision making.
7. IPCC. Summary for Policymakers, *in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner H.-O. et al.) (Cambridge Univ. Press, 2019).
8. Meredith, M. et al. Polar Regions, in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H.-O. et al.) 203–320 (Cambridge Univ. Press, 2019).
9. Fox-Kemper, B. et al. Ocean, Cryosphere and Sea Level Change, in *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 1211–1362 (Cambridge Univ. Press, 2021).
10. Constable, A. J. et al. Cross-Chapter Paper 6: Polar Regions, in *Climate Change 2022: Impacts, Adaptation and Vulnerability* (eds Pörtner, H.-O. et al.) 2319–2368 (Cambridge Univ. Press, 2022).
11. Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J. & Phillips, T. Recent changes in Antarctic Sea Ice. *Phil. Trans. R. Soc. A* **373**, 20140163 (2015).
12. Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B. & Katsman, C. A. Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nat. Geosci.* **6**, 376–379 (2013).
13. Holland, P. R. & Kwok, R. Wind-driven trends in Antarctic sea-ice drift. *Nat. Geosci.* **5**, 872–875 (2012).
14. Ferreira, D., Marshall, J., Bitz, C. M., Solomon, S. & Plumb, A. Antarctic Ocean and sea ice response to ozone depletion: a two-time-scale problem. *J. Clim.* **28**, 1206–1226 (2015).
15. Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D. & Chang, K.-L. A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature* **579**, 544–548 (2020).
16. Schroeter, S., O'Kane, T. J. & Sandery, P. A. Antarctic sea ice regime shift associated with decreasing zonal symmetry in the Southern Annular Mode. *The Cryosphere* **17**, 701–717 (2023).
17. Siegert, M. J. et al. Antarctic extreme events. *Front. Environ. Sci.* https://doi.org/10.3389/fenvs.2023.1229283 (2023).
18. Gilbert, E. & Holmes, C. 2023's Antarctic sea ice extent is the lowest on record. *Weather* **79**, 46–51 (2024).
19. Purich, A. & Doddridge, E. W. Record low Antarctic sea ice coverage indicates a new sea ice state. *Commun. Earth Environ.* **4**, 314 (2023).
This influential study demonstrates that Antarctic sea ice has shifted to a new low sea-ice state, and connects this regime shift to the confluence with subsurface warming of the Southern Ocean.
20. Hobbs, W. et al. Observational evidence for a regime shift in summer Antarctic sea ice. *J. Clim.* **37**, 2263–2275 (2024).
21. Fogt, R. L., Sleinkofer, A. M., Raphael, M. N. & Handcock, M. S. A regime shift in seasonal total Antarctic sea ice extent in the twentieth century. *Nat. Clim. Change* **12**, 54–62 (2022).
This study developed an observation-based reconstruction of Antarctic sea-ice extent that demonstrated the increase in Antarctic sea ice during the satellite era was unusual in a twentieth century context, and also provides a basis for demonstrating the extraordinary nature of abrupt sea-ice loss since 2014.
22. Dalaiden, Q. et al. An unprecedented sea ice retreat in the Weddell Sea driving an overall decrease of the Antarctic sea-ice extent over the 20th century. *Geophys. Res. Lett.* **50**, e2023GL104666 (2023).
23. Goosse, H., Dalaiden, Q., Feba, F., Mezzina, B. & Fogt, R. L. A drop in Antarctic sea ice extent at the end of the 1970s. *Commun. Earth Environ.* **5**, 628 (2024).
24. Raphael, M. N., Maierhofer, T. J., Fogt, R. L., Hobbs, W. R. & Handcock, M. S. A twenty-first century structural change in Antarctica's sea ice system. *Commun. Earth Environ.* **6**, 131 (2025).
25. Maierhofer, T. J., Raphael, M. N., Fogt, R. L. & Handcock, M. S. A Bayesian model for 20th century Antarctic sea ice extent reconstruction. *Earth Space Sci.* **11**, e2024EA003577 (2024).
26. Morioka, Y. et al. Antarctic sea ice multidecadal variability triggered by Southern Annular Mode and deep convection. *Commun. Earth Environ.* **5**, 633 (2024).
27. Boers, N. Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Change* **11**, 680–688 (2021).
28. Dakos, V. et al. Tipping point detection and early warnings in climate, ecological, and human systems. *Earth Syst. Dynam.* **15**, 1117–1135 (2024).
29. Espinosa, Z. I., Blanchard-Wrigglesworth, E. & Bitz, C. M. Understanding the drivers and predictability of record low Antarctic sea ice in austral winter 2023. *Commun. Earth Environ.* **5**, 723 (2024).
30. Zhang, L. et al. The relative role of the subsurface Southern Ocean in driving negative Antarctic Sea ice extent anomalies in 2016–2021. *Commun. Earth Environ.* **3**, 302 (2022).
31. Himmich, K. et al. Thermodynamics drive post-2016 changes in the Antarctic sea ice seasonal cycle. *J. Geophys. Res. Oceans* **129**, e2024JC021112 (2024).
32. Lenton, T. M. et al. Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105**, 1786–1793 (2008).
33. Chamberlain, M. A., Ziehn, T. & Law, R. M. The Southern Ocean as the climate's freight train—driving ongoing global warming under zero-emission scenarios with ACCESS-ESM1.5. *Biogeosciences* **21**, 3053–3073 (2024).
34. King, A. D. et al. Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5. *Earth Syst. Dynam.* **15**, 1353–1383 (2024).

35. Morioka, Y. et al. Role of anthropogenic forcing in Antarctic sea ice variability simulated in climate models. *Nat. Commun.* **15**, 10511 (2024).
36. King, A. D., Abram, N. J., Alastrué de Asenjo, E. & Ziehn, T. ESD Ideas: Extended net zero simulations are critical for informed decision making. *EGUsphere* https://doi.org/10.5194/egusphere-2025-903 (2025).
37. Holmes, C. R., Bracegirdle, T. J., Holland, P. R., Stroeve, J. & Wilkinson, J. New perspectives on the skill of modelled sea ice trends in light of recent Antarctic sea ice loss. *Cryosphere* **18**, 5641–5652 (2024).
This paper demonstrates that recent unprecedented Antarctic sea-ice loss challenges the skill of current climate models in accurately predicting sea-ice trends, emphasizing the urgent need for model refinements to better capture potential abrupt changes.
38. Duspayev, A., Flanner, M. G. & Riihelä, A. Earth's sea ice radiative effect from 1980 to 2023. *Geophys. Res. Lett.* **51**, e2024GL109608 (2024).
39. Rantanen, M. et al. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* **3**, 168 (2022).
40. Vogt, L. et al. Increased future ocean heat uptake constrained by Antarctic sea ice extent. Preprint at *Res. Sq.* https://doi.org/10.21203/rs.3.rs-3982037/v2 (2025).
41. England, M. R., Polvani, L. M., Sun, L. & Deser, C. Tropical climate responses to projected Arctic and Antarctic sea-ice loss. *Nat. Geosci.* **13**, 275–281 (2020).
42. Ayres, H. C., Screen, J. A., Blockley, E. W. & Bracegirdle, T. J. The coupled atmosphere–ocean response to Antarctic sea ice loss. *J. Clim.* **35**, 4665–4685 (2022).
43. Zhou, S. et al. Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes. *Nat. Clim. Change* **13**, 701–709 (2023).
44. Silvano, A. et al. Recent recovery of Antarctic Bottom Water formation in the Ross Sea driven by climate anomalies. *Nat. Geosci.* **13**, 780–786 (2020).
45. Josey, S. A. et al. Record-low Antarctic sea ice in 2023 increased ocean heat loss and storms. *Nature* **636**, 635–639 (2024).
46. Reid, P. A. & Massom, R. A. Change and variability in Antarctic coastal exposure, 1979–2020. *Nat. Commun.* **13**, 1164 (2022).
47. Fretwell, P. T., Boutet, A. & Ratcliffe, N. Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. *Commun. Earth Environ.* **4**, 273 (2023).
The catastrophic regional-scale breeding failure of emperor penguins in 2022 due to record low Antarctic sea ice underscores the vulnerability of polar ecosystems to climate-driven abrupt change, highlighting the potential for irreversible ecological shifts.
48. Kawaguchi, S. et al. Climate change impacts on Antarctic krill behaviour and population dynamics. *Nat. Rev. Earth Environ.* **5**, 43–58 (2024).
49. McManus, J. F., Francois, R., Gherardi, J. M., Keigwin, L. D. & Brown-Leger, S. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* **428**, 834–837 (2004).
50. Abernathey, R. P. et al. Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nat. Geosci.* **9**, 596–601 (2016).
51. Heuzé, C. Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models. *Ocean Sci.* **17**, 59–90 (2021).
52. Purich, A. & England, M. H. Historical and future projected warming of Antarctic Shelf Bottom Water in CMIP6 models. *Geophys. Res. Lett.* **48**, e2021GL092752 (2021).
53. de Lavergne, C., Palter, J. B., Galbraith, E. D., Bernardello, R. & Marinov, I. Cessation of deep convection in the open Southern Ocean under anthropogenic climate change. *Nat. Clim. Change* **4**, 278–282 (2014).
54. Lago, V. & England, M. H. Projected slowdown of Antarctic Bottom Water formation in response to amplified meltwater contributions. *J. Clim.* **32**, 6319–6335 (2019).
55. Li, Q., England, M. H., Hogg, A. M., Rintoul, S. R. & Morrison, A. K. Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* **615**, 841–847 (2023).
Using a high-resolution ocean model that captures the four known regions of Antarctic Bottom Water formation, this study projects a 40% slowdown of the Antarctic Overturning Circulation by 2050 in response to expected increases in Antarctic meltwater.
56. Huneke, W. G. C., Hobbs, W. R., Klocker, A. & Naughten, K. A. Dynamic response to ice shelf basal meltwater relevant to explain observed sea ice trends near the Antarctic Continental Shelf. *Geophys. Res. Lett.* **50**, e2023GL105435 (2023).
57. Jacobs, S. S., Giulivi, C. F. & Dutrieux, P. Persistent Ross Sea freshening from imbalance West Antarctic ice shelf melting. *J. Geophys. Res. Oceans* **127**, e2021JC017808 (2022).
58. Gunn, K. L., Rintoul, S. R., England, M. H. & Bowen, M. M. Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin. *Nat. Clim. Change* **13**, 537–544 (2023).
Observations from the Australian Antarctic Basin show that over recent decades there has been a reduction in Antarctic Bottom Water transport, coincident with a strong freshening on the continental shelf; this finding is reinforced by equivalent observations from the Weddell sector (ref. 43).
59. Schmidt, C., Morrison, A. K. & England, M. H. Wind- and sea-ice-driven interannual variability of Antarctic Bottom Water formation. *J. Geophys. Res. Oceans* **128**, e2023JC019774 (2023).
60. Adkins, J. F. The role of deep ocean circulation in setting glacial climates. *Paleoceanography* **28**, 539–561 (2013).
61. Ferrari, R. et al. Antarctic sea ice control on ocean circulation in present and glacial climates. *Proc. Natl Acad. Sci. USA* **111**, 8753–8758 (2014).
62. Burke, A. & Robinson, L. F. The Southern Ocean's role in carbon exchange during the Last Deglaciation. *Science* **335**, 557–561 (2012).
63. Skinner, L. C., Fallon, S., Waelbroeck, C., Michel, E. & Barker, S. Ventilation of the deep Southern Ocean and deglacial CO_2 rise. *Science* **328**, 1147–1151 (2010).
64. Rae, J. W. B. et al. CO_2 storage and release in the deep Southern Ocean on millennial to centennial timescales. *Nature* **562**, 569–573 (2018).
65. Huang, H., Gutjahr, M., Eisenhauer, A. & Kuhn, G. No detectable Weddell Sea Antarctic Bottom Water export during the Last and Penultimate Glacial Maximum. *Nat. Commun.* **11**, 424 (2020).
66. Weber, M. E. et al. Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation. *Nature* **510**, 134–138 (2014).
67. Yeung, N. K. H., Menviel, L., Meissner, K. J. & Sikes, E. Assessing the spatial origin of meltwater pulse 1A using oxygen-isotope fingerprinting. *Paleoceanogr. Paleoclimatol.* **34**, 2031–2046 (2019).
68. Golledge, N. R. et al. Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. *Nat. Commun.* **5**, 5107 (2014).
69. Turney, C. S. M. et al. Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica. *Proc. Natl Acad. Sci. USA* **117**, 3996–4006 (2020).
70. Blackburn, T. et al. Ice retreat in Wilkes Basin of East Antarctica during a warm interglacial. *Nature* **583**, 554–559 (2020).
71. Hayes, C. T. et al. A stagnation event in the deep South Atlantic during the last interglacial period. *Science* **346**, 1514–1517 (2014).
72. Glasscock, S. K., Hayes, C. T., Redmond, N. & Rohde, E. Changes in Antarctic Bottom Water formation during interglacial periods. *Paleoceanogr. Paleoclimatol.* **35**, e2020PA003867 (2020).
73. Rohling, E. J. et al. Asynchronous Antarctic and Greenland ice-volume contributions to the last interglacial sea-level highstand. *Nat. Commun.* **10**, 5040 (2019).
74. Yeung, N. K.-H. et al. Last Interglacial subsurface warming on the Antarctic shelf triggered by reduced deep-ocean convection. *Commun. Earth Environ.* **5**, 212 (2024).
75. Bronselaer, B. et al. Change in future climate due to Antarctic meltwater. *Nature* **564**, 53–58 (2018).
Global climate impacts of Antarctic meltwater are shown to be far-reaching using a coupled climate model, identifying global surface temperature changes, shifting tropical precipitation and subsurface warming around the Antarctic margins that may accelerate ice shelf basal melting.
76. Ribeiro, N. et al. Warm modified Circumpolar Deep Water intrusions drive ice shelf melt and inhibit dense shelf water formation in Vincennes Bay, East Antarctica. *J. Geophys. Res. Oceans* **126**, e2020JC016998 (2021).
77. Rintoul, S. R. et al. Ocean heat drives rapid basal melt of the Totten Ice Shelf. *Sci. Adv.* **2**, e1601610 (2016).
78. Adusumilli, S., Fricker, H. A., Medley, B., Padman, L. & Siegfried, M. R. Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves. *Nat. Geosci.* **13**, 616–620 (2020).
79. Naughten, K. A., Holland, P. R. & De Rydt, J. Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. *Nat. Clim. Change* **13**, 1222–1228 (2023).
Regional ocean modelling finds rapid ocean warming in the Amundsen Sea for a range of different emission scenarios, suggesting that future mitigation efforts cannot prevent ocean-driven melting of ice shelves in this region.
80. Ribeiro, N. et al. Oceanic regime shift to a warmer continental shelf adjacent to the Shackleton Ice Shelf, East Antarctica. *J. Geophys. Res. Oceans* **128**, e2023JC019882 (2023).
81. Mathiot, P. & Jourdain, N. C. Southern Ocean warming and Antarctic ice shelf melting in conditions plausible by late 23rd century in a high-end scenario. *Ocean Sci.* **19**, 1595–1615 (2023).
82. Gottschalk, J. et al. Biological and physical controls in the Southern Ocean on past millennial-scale atmospheric CO_2 changes. *Nat. Commun.* **7**, 11539 (2016).
83. Long, M. C. et al. Strong Southern Ocean carbon uptake evident in airborne observations. *Science* **374**, 1275–1280 (2021).
84. Liu, Y., Moore, J. K., Primeau, F. & Wang, W. L. Reduced CO_2 uptake and growing nutrient sequestration from slowing overturning circulation. *Nat. Clim. Change* **13**, 83–90 (2023).
85. Dong, Y., Pauling, A. G., Sadai, S. & Armour, K. C. Antarctic ice-sheet meltwater reduces transient warming and climate sensitivity through the sea-surface temperature pattern effect. *Geophys. Res. Lett.* **49**, e2022GL101249 (2022).
86. Shin, S.-J. et al. Southern Ocean control of 2 °C global warming in climate models. *Earth Future* **11**, e2022EF003212 (2023).
87. Garbe, J., Albrecht, T., Levermann, A., Donges, J. F. & Winkelmann, R. The hysteresis of the Antarctic Ice Sheet. *Nature* **585**, 538–544 (2020).
88. Rosier, S. H. R. et al. The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. *Cryosphere* **15**, 1501–1516 (2021).
89. Pattyn, F. & Morlighem, M. The uncertain future of the Antarctic Ice Sheet. *Science* **367**, 1331–1335 (2020).
90. Schoof, C. Ice sheet grounding line dynamics: steady states, stability, and hysteresis. *J. Geophys. Res. Earth Surf.* https://doi.org/10.1029/2006JF000664 (2007).
91. Weertman, J. Stability of the junction of an ice sheet and an ice shelf. *J. Glaciol.* **13**, 3–11 (1974).
92. Stokes, C. R. et al. Response of the East Antarctic Ice Sheet to past and future climate change. *Nature* **608**, 275–286 (2022).
This paper reveals the potential vulnerability of the East Antarctic Ice Sheet to past and future climate change, highlighting its contribution to sea-level rise and underscoring the importance of understanding ice sheet dynamics in the context of climate tipping points.
93. Dutton, A. & Lambeck, K. Ice volume and sea level during the Last Interglacial. *Science* **337**, 216–219 (2012).
94. Dumitru, O. A. et al. Last interglacial global mean sea level from high-precision U-series ages of Bahamian fossil coral reefs. *Quat. Sci. Rev.* **318**, 108287 (2023).
95. Lau, S. C. Y. et al. Genomic evidence for West Antarctic Ice Sheet collapse during the Last Interglacial. *Science* **382**, 1384–1389 (2023).
This study uses novel genetic indicators to infer that the West Antarctic Ice Sheet underwent major collapse during the last warm period in Earth's past when global temperatures were similar to present day.
96. Wolff, E. W. et al. The Ronne Ice Shelf survived the last interglacial. *Nature* **638**, 133–137 (2025).
97. Iizuka, M. et al. Multiple episodes of ice loss from the Wilkes Subglacial Basin during the Last Interglacial. *Nat. Commun.* **14**, 2129 (2023).
98. Hutchinson, D. K., Menviel, L., Meissner, K. J. & Hogg, A. M. East Antarctic warming forced by ice loss during the Last Interglacial. *Nat. Commun.* **15**, 1026 (2024).
99. DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**, 591–597 (2016).

100. Otosaka, I. N. et al. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth Syst. Sci. Data* **15**, 1597–1616 (2023).
101. Rignot, E. et al. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proc. Natl Acad. Sci. USA* **116**, 1095–1103 (2019).
102. Shepherd, A. et al. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* **558**, 219–222 (2018).
103. Smith, B. et al. Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science* **368**, 1239–1242 (2020).
104. Gudmundsson, G. H., Paolo, F. S., Adusumilli, S. & Fricker, H. A. Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves. *Geophys. Res. Lett.* **46**, 13903–13909 (2019).
105. Reese, R., Gudmundsson, G. H., Levermann, A. & Winkelmann, R. The far reach of ice-shelf thinning in Antarctica. *Nat. Clim. Change* **8**, 53–57 (2018).
106. Konrad, H. et al. Net retreat of Antarctic glacier grounding lines. *Nat. Geosci.* **11**, 258–262 (2018).
107. Milillo, P. et al. Rapid glacier retreat rates observed in West Antarctica. *Nat. Geosci.* **15**, 48–53 (2022).
108. Favier, L. et al. Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nat. Clim. Change* **4**, 117–121 (2014).
109. Joughin, I., Smith, B. E. & Medley, B. Marine ice sheet collapse potentially underway for the Thwaites Glacier Basin, West Antarctica. *Science* **344**, 735–738 (2014).
110. Mouginot, J., Rignot, E. & Scheuchl, B. Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophys. Res. Lett.* **41**, 1576–1584 (2014).
111. Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. & Scheuchl, B. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith and Kohler glaciers, West Antarctica from 1992 to 2011. *Geophys. Res. Lett.* **41**, 3502–3509 (2014).
112. Ritz, C. et al. Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature* **528**, 115–118 (2015).
113. Christie, F. D. W., Steig, E. J., Gourmelen, N., Tett, S. F. B. & Bingham, R. G. Inter-decadal climate variability induces differential ice response along Pacific-facing West Antarctica. *Nat. Commun.* **14**, 93 (2023).
114. Hill, E. A. et al. The stability of present-day Antarctic grounding lines, part 1: No indication of marine ice sheet instability in the current geometry. *Cryosphere* **17**, 3739–3759 (2023).
115. Reese, R. et al. The stability of present-day Antarctic grounding lines, part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded. *Cryosphere* **17**, 3761–3783 (2023).
This paper investigates the committed evolution of Antarctic grounding lines under the present-day climate, finding irreversible retreat in the Amundsen Sea Embayment is initiated within centuries but is not yet inevitable.
116. Sun, S. et al. Antarctic ice sheet response to sudden and sustained ice-shelf collapse (ABUMIP). *J. Glaciol.* **66**, 891–904 (2020).
117. Möller, T. et al. Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nat. Commun.* **15**, 6192 (2024).
118. Seroussi, H. et al. Evolution of the Antarctic Ice Sheet over the next three centuries from an ISMIP6 model ensemble. *Earth Future* **12**, e2024EF004561 (2024).
This contribution provides multi-century projections of the Antarctic Ice Sheet evolution using an ensemble of ice sheet models, revealing a sharp increase in mass loss and uncertainty from 2100 associated with anthropogenic climate change.
119. Scambos, T. A., Hulbe, C., Fahnestock, M. & Bohlander, J. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *J. Glaciol.* **46**, 516–530 (2000).
120. Lai, C.-Y. et al. Vulnerability of Antarctica's ice shelves to meltwater-driven fracture. *Nature* **584**, 574–578 (2020).
121. Cook, A. J. & Vaughan, D. G. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *Cryosphere* **4**, 77–98 (2010).
122. De Angelis, H. & Skvarca, P. Glacier surge after ice shelf collapse. *Science* **299**, 1560–1562 (2003).
123. Wuite, J. et al. Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013. *Cryosphere* **9**, 957–969 (2015).
124. Rott, H. et al. Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016. *Cryosphere* **12**, 1273–1291 (2018).
125. Trusel, L. D. et al. Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. *Nat. Geosci.* **8**, 927–932 (2015).
126. Gilbert, E. & Kittel, C. Surface melt and runoff on Antarctic ice shelves at 1.5 °C, 2 °C, and 4 °C of future warming. *Geophys. Res. Lett.* **48**, e2020GL091733 (2021).
127. Dell, R. L., Willis, I. C., Arnold, N. S., Banwell, A. F. & de Roda Husman, S. Substantial contribution of slush to meltwater area across Antarctic ice shelves. *Nat. Geosci.* **17**, 624–630 (2024).
128. Walker, C. C. et al. Multi-decadal collapse of East Antarctica's Conger–Glenzer Ice Shelf. *Nat. Geosci.* **17**, 1240–1248 (2024).
129. Wille, J. D. et al. The extraordinary March 2022 East Antarctica "heat" wave. Part II: Impacts on the Antarctic Ice Sheet. *J. Clim.* **37**, 779–799 (2024).
130. Hill, E. A., Gudmundsson, G. H. & Chandler, D. M. Ocean warming as a trigger for irreversible retreat of the Antarctic ice sheet. *Nat. Clim. Change* **14**, 1165–1171 (2024).
131. Ben-Yami, M., Skiba, V., Bathiany, S. & Boers, N. Uncertainties in critical slowing down indicators of observation-based fingerprints of the Atlantic Overturning Circulation. *Nat. Commun.* **14**, 8344 (2023).
132. Smith, R. S. et al. Coupling the U.K. Earth System Model to dynamic models of the Greenland and Antarctic Ice Sheets. *J. Adv. Model. Earth Syst.* **13**, e2021MS002520 (2021).
133. Zhou, Q. et al. Evaluating an accelerated forcing approach for improving computational efficiency in coupled ice sheet-ocean modelling. *Geosci. Model Dev. Discuss.* **17**, 8243–8265 (2024).
134. Miles, B. W. J. & Bingham, R. G. Progressive unanchoring of Antarctic ice shelves since 1973. *Nature* **626**, 785–791 (2024).
135. Bradley, A. T. & Hewitt, I. J. Tipping point in ice-sheet grounding-zone melting due to ocean water intrusion. *Nat. Geosci.* **17**, 631–637 (2024).
136. Larour, E. et al. Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks. *Science* **364**, eaav7908 (2019).
137. Kachuck, S. B., Martin, D. F., Bassis, J. N. & Price, S. F. Rapid viscoelastic deformation slows marine ice sheet instability at Pine Island Glacier. *Geophys. Res. Lett.* **47**, e2019GL086446 (2020).
138. Houriez, L. et al. Capturing solid earth and ice sheet interactions: insights from reinforced ridges in Thwaites Glacier. *EGUsphere* https://doi.org/10.5194/egusphere-2024-4136 (2025).
139. Wunderling, N., Donges, J. F., Kurths, J. & Winkelmann, R. Interacting tipping elements increase risk of climate domino effects under global warming. *Earth Syst. Dynam.* **12**, 601–619 (2021).
140. Rosser, J. P., Winkelmann, R. & Wunderling, N. Polar ice sheets are decisive contributors to uncertainty in climate tipping projections. *Commun. Earth Environ.* **5**, 702 (2024).
141. Seroussi, H. et al. Insights into the vulnerability of Antarctic glaciers from the ISMIP6 ice sheet model ensemble and associated uncertainty. *Cryosphere* **17**, 5197–5217 (2023).
142. Ehrenfeucht, S., Dow, C., McArthur, K., Morlighem, M. & McCormack, F. S. Antarctic wide subglacial hydrology modeling. *Geophys. Res. Lett.* **52**, e2024GL111386 (2025).
143. Graham, F. S. et al. A high-resolution synthetic bed elevation grid of the Antarctic continent. *Earth Syst. Sci. Data* **9**, 267–279 (2017).
144. Paxman, G. J. G., Gasson, E. G. W., Jamieson, S. S. R., Bentley, M. J. & Ferraccioli, F. Long-term increase in Antarctic Ice Sheet vulnerability driven by bed topography evolution. *Geophys. Res. Lett.* **47**, e2020GL090003 (2020).
145. Castleman, B. A., Schlegel, N.-J., Caron, L., Larour, E. & Khazendar, A. Derivation of bedrock topography measurement requirements for the reduction of uncertainty in ice-sheet model projections of Thwaites Glacier. *Cryosphere* **16**, 761–778 (2022).
146. Reading, A. M. et al. Antarctic geothermal heat flow and its implications for tectonics and ice sheets. *Nat. Rev. Earth. Environ.* **3**, 814–831 (2022).
147. Stål, T., Reading, A. M., Halpin, J. A. & Whittaker, J. M. Antarctic geothermal heat flow model: Aq1. *Geochem. Geophys. Geosyst.* **22**, e2020GC009428 (2021).
148. Ivins, E. R., van der Wal, W., Wiens, D. A., Lloyd, A. J. & Caron, L. in *The Geochemistry and Geophysics of the Antarctic Mantle* (eds A. P. Martin & W. van der Wal) (Geological Society of London, 2023).
149. Whitehouse, P. L., Gomez, N., King, M. A. & Wiens, D. A. Solid Earth change and the evolution of the Antarctic Ice Sheet. *Nat. Commun.* **10**, 503 (2019).
150. Lee, J. R. et al. Threat management priorities for conserving Antarctic biodiversity. *PLoS Biol.* **20**, e3001921 (2022).
151. Griffiths, H. J., Cummings, V. J., Van de Putte, A., Whittle, R. J. & Waller, C. L. Antarctic benthic ecological change. *Nat. Rev. Earth Environ.* **5**, 645–664 (2024).
A comprehensive summary of abrupt changes that are threatening cold-adapted species in the benthic communities around Antarctica due to warming, ocean acidification and cryospheric changes.
152. Banyard, A. C. et al. Detection and spread of high pathogenicity avian influenza virus H5N1 in the Antarctic region. *Nat. Commun.* **15**, 7433 (2024).
153. Wienecke, B., Lieser, J. L., McInnes, J. C. & Barrington, J. H. S. Fast ice variability in East Antarctica: observed repercussions for emperor penguins. *Endang. Species Res.* **55**, 1–19 (2024).
154. Ingels, J. et al. Antarctic ecosystem responses following ice-shelf collapse and iceberg calving: science review and future research. *WIREs Clim. Change* **12**, e682 (2021).
155. Clark, G. F. et al. Light-driven tipping points in polar ecosystems. *Global Change Biol.* **19**, 3749–3761 (2013).
156. Sahade, R. et al. Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. *Sci. Adv.* **1**, e1500050 (2015).
157. Clark, G. F., Stark, J. S., Palmer, A. S., Riddle, M. J. & Johnston, E. L. The roles of sea-ice, light and sedimentation in structuring shallow Antarctic benthic communities. *PLoS ONE* **12**, e0168391 (2017).
158. Dayton, P. K. et al. Benthic responses to an Antarctic regime shift: food particle size and recruitment biology. *Ecol. Appl.* **29**, e01823 (2019).
159. Prather, H. M. et al. Species-specific effects of passive warming in an Antarctic moss system. *R. Soc. Open Sci.* **6**, 190744 (2019).
160. Roland, T. P. et al. Sustained greening of the Antarctic Peninsula observed from satellites. *Nat. Geosci.* **17**, 1121–1126 (2024).
161. Bokhorst, S. et al. Greening rates are sensitive to methodology and biology; comment to sustained greening of the Antarctic Peninsula observed from satellites. Preprint at *bioRxiv* https://doi.org/10.1101/2024.11.07.622227 (2024).
162. Cannone, N., Malfasi, F., Favero-Longo, S. E., Convey, P. & Guglielmin, M. Acceleration of climate warming and plant dynamics in Antarctica. *Curr. Biol.* **32**, 1599–1606.e1592 (2022).
163. Robinson, S. A. et al. Rapid change in East Antarctic terrestrial vegetation in response to regional drying. *Nat. Clim. Change* **8**, 879–884 (2018).
164. Lee, J. R. et al. Islands in the ice: potential impacts of habitat transformation on Antarctic biodiversity. *Global Change Biol.* **28**, 5865–5880 (2022).
165. Bergstrom, D. M. et al. Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biol.* **27**, 1692–1703 (2021).
This perspective underscores the interconnectedness of global ecosystems by demonstrating that ecosystem collapse, from the tropics to the Antarctic, necessitates urgent and comprehensive strategies to mitigate cascading abrupt changes.
166. Fraser, A. D. et al. Antarctic Landfast Sea Ice: a review of its physics, biogeochemistry and ecology. *Rev. Geophys.* **61**, e2022RG000770 (2023).
This review addresses Antarctic land-fast sea ice, highlighting its critical role in regional physics, biogeochemistry and ecology, and emphasizing the potential consequences of its rapid decline.
167. Jenouvrier, S. et al. The call of the emperor penguin: legal responses to species threatened by climate change. *Global Change Biol.* **27**, 5008–5029 (2021).
168. Fretwell, P. T. A 6 year assessment of low sea-ice impacts on emperor penguins. *Antarct. Sci.* **36**, 3–5 (2024).

169. Fretwell, P. T. & Trathan, P. N. Emperors on thin ice: three years of breeding failure at Halley Bay. *Antarct. Sci.* **31**, 133–138 (2019).
170. Corso, A. D., Steinberg, D. K., Stammerjohn, S. E. & Hilton, E. J. Climate drives long-term change in Antarctic silverfish along the western Antarctic Peninsula. *Commun. Biol.* **5**, 104 (2022).
171. Schmidt, A. E. et al. Sea ice concentration decline in an important Adélie penguin molt area. *Proc. Natl Acad. Sci. USA* **120**, e2306840120 (2023).
172. Fernández-Barba, M., Belyaev, O., Huertas, I. E. & Navarro, G. Marine heatwaves in a shifting Southern Ocean induce dynamical changes in primary production. *Commun. Earth Environ.* **5**, 404 (2024).
173. Boyd, P. W. Physiology and iron modulate diverse responses of diatoms to a warming Southern Ocean. *Nat. Clim. Change* **9**, 148–152 (2019).
174. Boyd, P. W. et al. The role of biota in the Southern Ocean carbon cycle. *Nat. Rev. Earth Environ.* **5**, 390–408 (2024).
175. Hancock, A. M., King, C. K., Stark, J. S., McMinn, A. & Davidson, A. T. Effects of ocean acidification on Antarctic marine organisms: a meta-analysis. *Ecol. Evol.* **10**, 4495–4514 (2020).
176. Nissen, C. et al. Severe 21st-century ocean acidification in Antarctic Marine Protected Areas. *Nat. Commun.* **15**, 259 (2024).
177. Hayward, A. et al. Antarctic phytoplankton communities restructure under shifting sea-ice regimes. *Nat. Clim. Change*, https://doi.org/10.1038/s41558-025-02379-x (2025).
178. Jones, J. M. et al. Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nat. Clim. Change* **6**, 917–926 (2016).
179. Abram, N. J. et al. Early onset of industrial-era warming across the oceans and continents. *Nature* **536**, 411–418 (2016).
180. Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A. & Newsom, E. R. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nat. Geosci.* **9**, 549–554 (2016).
181. Naughten, K. A. et al. Two-timescale response of a large Antarctic ice shelf to climate change. *Nat. Commun.* **12**, 1991 (2021).
182. Rackow, T. et al. Delayed Antarctic sea-ice decline in high-resolution climate change simulations. *Nat. Commun.* **13**, 637 (2022).
183. Beckmann, J. & Winkelmann, R. Effects of extreme melt events on ice flow and sea level rise of the Greenland Ice Sheet. *Cryosphere* **17**, 3083–3099 (2023).
184. Kubiszewski, I. et al. Cascading tipping points of Antarctica and the Southern Ocean. *Ambio* **54**, 642–659 (2025).
185. Hughes, K. A., Convey, P. & Turner, J. Developing resilience to climate change impacts in Antarctica: an evaluation of Antarctic Treaty System protected area policy. *Environ. Sci. Policy* **124**, 12–22 (2021).
186. Brooks, C. M. et al. Protect global values of the Southern Ocean ecosystem. *Science* **378**, 477–479 (2022).
187. Siegert, M. et al. Safeguarding the polar regions from dangerous geoengineering: a crticial assessment of current projects and future prospects. *Front. Sci.* Preprint at https://doi.org/10.13140/RG.2.2.13179.94246 (in the press).
The urgency of human-caused climate change and the potential abrupt and irreversibile global impacts of polar changes is sparking pressures for polar geoengineering solutions, but this paper assesses that these are not feasible and may instead be environmentally dangerous.
188. Fankhauser, S. et al. The meaning of net zero and how to get it right. *Nat. Clim. Change* **12**, 15–21 (2022).
189. Forster, P. M. et al. Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **16**, 2625–2658 (2024).
190. Matthews, H. D. et al. Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nat. Geosci.* **13**, 769–779 (2020).
191. Moorman, R., Morrison, A. K. & McC. Hogg, A. Thermal responses to Antarctic Ice Shelf melt in an eddy-rich global ocean–sea ice model. *J. Clim.* **33**, 6599–6620 (2020).

Methods

Satellite sea-ice data used in this paper are derived from the National Snow and Ice Data Centre (NSIDC). We use the Sea Ice Index v.3.0 for sea-ice extent in the Southern Hemisphere (Figs. 1 and 2 and Extended Data Figs. 2 and 5), Northern Hemisphere (Fig. 2 and Extended Data Fig. 5), Antarctic regions (Extended Data Fig. 4), and sea-ice extent monthly and 1981–2010 median shape files[192] (Fig. 1b,c, and Extended Data Fig. 4). Datasets accessed at https://nsidc.org/data/g02135/versions/3. The NSIDC defines sea-ice extent based on grid cells where the concentration of sea ice is 15% or greater. The gridded NSIDC sea-ice concentration data from the Climate Data Record (CDR) passive microwave v.4 dataset[193] for the Southern Hemisphere were used to calculate sea-ice extent for proxy-based reconstruction regions using the area sum of grid cells exceeding 15% sea-ice concentration (Extended Data Fig. 3). Datasets were accessed at https://nsidc.org/data/g02202/versions/4.

We express sea-ice anomalies relative to a 1981–2010 climatology. This follows World Meteorological Organisation (WMO) recommendations to use a 30-year long interval as a reference climatology, with 1981–2010 representing the earliest possible WMO 'climatological standard normal' interval that is possible for satellite-derived sea-ice observations which begin in 1978.

Sea-ice radiative effect

Figure 2c uses data from the MERRA-AnnVar analysis of ref. 38 for the Northern Hemisphere (Arctic) and Southern Hemisphere (Antarctic), using monthly and annually varying atmospheric fields of the MERRA2 dataset. Other versions of the sea-ice radiative effect based on different datasets produce comparable results to those shown in Fig. 2c. Data accessed by personal request.

Historical sea-ice data and proxy-based reconstructions

The sea-ice extent reconstruction used in Fig. 1d,e is derived from atmospheric temperature and pressure observations as well as indices of climate variability[21,194], using the best-fit reconstruction for total Antarctic sea-ice extent. The reconstructions are derived at seasonal resolution from 1905 to 2020. Of the 464 seasons in the best-fit sea-ice reconstruction, none fall below -3σ of the observed 1981–2010 climatology. Across all ensemble members of the total Antarctic sea-ice reconstruction there are 3,480 seasons, and only 16 fall below -3σ of the observed 1981–2010 climatology (and none are below -6σ). In comparison, 7 out of the 8 seasons since summer of 2022/23 have had sea-ice anomalies below -3σ of the observed 1981–2010 climatology, 4 out of 8 have been below -4σ, 3 out of 8 have been below -5σ, and 1 (winter of 2023) has been below -6σ. Reconstruction datasets accessed at https://doi.org/10.6084/m9.figshare.c.5709767.

The annual resolution Southern Hemisphere sea-ice extent reconstruction from 1700–2000 that is used in Extended Data Fig. 2a is based on a network of Antarctic ice-core and Southern Hemisphere tree-ring proxy records assimilated with the isotope-enabled Community Earth system model[22,195]. The dataset accessed at https://doi.org/10.5281/zenodo.7966209 provides the ensemble mean reconstruction and the standard deviation across the ensemble members, but does not include all reconstruction ensemble members.

The monthly resolution Antarctic total sea-ice extent reconstruction from 1899–1978 used in Extended Data Fig. 2b is based on historical climate observations that are used alongside the satellite sea-ice extent record (the reconstruction prior) in a Bayesian framework to generate 2,500 equally plausible reconstructions of Antarctic sea ice[24,25,196]. Across the 2,392,500 reconstructed months (957 months for 2,500 reconstruction members), only 0.52% of months have anomalies below -3σ, only 0.0016% of months have anomalies below -6σ, and only 1 month has an anomaly below the -7.3σ level that was observed in July 2023. Data accessed at https://doi.org/10.5281/zenodo.7971734.

Regional sea-ice reconstructions used in Extended Data Figs. 2 and 3 are derived from the observational record of fast-ice duration from South Orkney[197,198] (dataset accessed at https://doi.org/10.5285/0313090c-373e-4e2e-97f2-6cd0d4138e75); methanesulphonic acid (MSA) record from the Ferrigno ice core[199,200] (dataset accessed at https://doi.org/10.5285/1f44795b-e596-433c-b69f-caf674880daa); Antarctic Peninsula stack of ice-core MSA records[201]; and the Law Dome (DSS) ice-core MSA record[202,203] (dataset accessed at https://doi.org/10.26179/5bf4b43fd4f45).

Sea ice under climate stabilization scenarios

Extended Data Figures 5 and 6 use data from net-zero emission driven simulations[34], including the associated data repository at https://doi.org/10.5281/zenodo.13168507.

Antarctic Overturning Circulation

Observed and modelled changes in the Antarctic Overturning Circulation are expressed as % change metrics to facilitate comparisons across the different datasets (Fig. 3).

Observed changes in the Weddell sector are based on observed percentage changes in Antarctic Bottom Water volume (from Table 1 of ref. 43). The percentage change over 1992–2020 is expressed as the average of CTD sections A12 and SR4 (−28.6% and −20.9%), while the uncertainty range is expressed as the sum of uncertainties (4.4% and 3.9%). Observed changes in the Australian–Antarctic sector over 1994–2017 are based on observations of Antarctic Bottom Water transport (from Fig. 4 of ref. 58), expressed as a percentage change based on the 1994 transport.

Modelled changes in Antarctic Overturning Circulation are defined as the strength of the abyssal cell of the overturning streamfunction (minimum below 2,500 m, 0–60°S). The CMIP6 multi-model mean and $\pm 1\sigma$ model spread is calculated across 18 models, where change in the abyssal cell strength is calculated relative to the 1981–2010 baseline. We also show the Antarctic Overturning Circulation for a high-resolution (0.1°) ocean–sea ice model (ACCESS-OM2)[55] that represents Antarctic Bottom Water via realistic dense shelf water overflows, run with anthropogenic forcings and Antarctic meltwater over 2001–2050. The ACCESS-OM2 circulation is expressed as the % change in abyssal cell strength relative to the control run.

Antarctic Ice Sheet indicative susceptibilities

We calculate indicative spatial vulnerability (Fig 4c) as:

$$\text{Vulnerability} = [\Sigma(\text{susceptibility above threshold})] \times [\Sigma(\text{observed change above threshold})]$$

Susceptibility factors (Fig. 4a), thresholded to Boolean values, include: bed slope above the continental median (BedMachine)[204]; ice-shelf buttressing (PISM)[116]; bed below present sea level (BedMachine)[204]; Pliocene ice extent[205]; geothermal flow above 58 mWm^{-2} (ref. 147); and sedimentary basin likelihood above median[206]. Observed change variables (Fig. 4b), also thresholded to Boolean values, comprise: albedo reduction above median amplitude[207]; air temperature increase (RACMO)[208]; surface lowering[209]; surface mass balance change above median from the least square trend 2022–1979 (RACMO2.3p2)[208]; ice-flow acceleration (MEaSUREs v.2)[101,210]; and mass loss (GMB; TUD 2024)[211]. Each continuous variable is converted to Boolean (1/0) by applying median thresholds, except for marine ice sheet (physical threshold of present sea level), surface lowering (negative values), temperature increase (positive values), and ice-flow acceleration (positive values). Vulnerability (Fig. 4c) aggregates these as the product of summed susceptibility and change components. For this indicative appraisal, the detailed datasets have been smoothed using a 30 km Gaussian kernel. Each threshold map is shown in Extended Data Fig. 8.

Emperor penguin data

Figure 5a–c shows years and locations where colonies experienced early fast-ice breakout events prior to chick fledging that would have resulted in increased or complete breeding failure of the colony. Breeding failure is inferred from satellite-derived imagery from days where colonies are not obscured by cloud cover. Data compiled from various studies[47,153,168,169,212,213].

Fast-ice data

Figure 5d shows Antarctic fast-ice extent in early to mid March (the fast-ice minimum) from 2000 to 2022. Data are derived from figure 13 of ref. 166, based on datasets available at https://doi.org/10.26179/g5pp-z960 and https://doi.org/10.26179/5d267d1ceb60c.

Software

Analysis and figures for Figs. 1, 2 and 5 and Extended Data Figs. 2–7 were produced using MATLAB (R2024a) software. This included using the M_Map mapping package[214] and the Climate Data Toolbox[215]. NCL (v.6.6.2) was used to produce Fig. 3b. The Python package agrid[216] was used to calculate and visualise ice-sheet vulnerability (Fig. 4 and Extended Data Fig. 8).

192. Fetterer, F., Knowles, K., Meier, W. N., Savoie, M. & Windnagel, A. K. Sea ice index, version 3 [Data Set]. *National Snow and Ice Data Center* https://doi.org/10.7265/N5K072F8 (2017).
193. Meier, W. N., Fetterer, F., Windnagel, A. K. & Stewart, J. S. NOAA/NSIDC climate data record of passive microwave sea ice concentration. (G02202, version 4). [Data Set]. *National Snow and Ice Data Center* https://doi.org/10.7265/efmz-2t65 (2021).
194. Fogt, R. Antarctic sea ice reconstructions, version 2. *Figshare* https://doi.org/10.6084/m9.figshare.c.5709767 (2021).
195. Dalaiden, Q. An unprecedented sea ice retreat in the Weddell Sea driving an overall decrease of the Antarctic sea-ice extent over the 20th century [Data set]. *Zenodo* https://doi.org/10.5281/zenodo.7966209 (2023).
196. Maierhofer, T. J., Raphael, M. N. & Handcock, M. 20th Century Antarctic sea ice extent anomaly reconstruction by sector. *Zenodo* https://doi.org/10.5281/zenodo.7971734 (2023).
197. Murphy, E. J., Clarke, A., Abram, N. J. & Turner, J. Variability of sea-ice in the northern Weddell Sea during the 20th century. *J. Geophys. Res. Oceans* **119**, 4549–4572 (2014).
198. Murphy, E., Dunn, M., Turner, J., Clarke, A. & Abram, N. South Orkney Fast-Ice Series (SOFI) (version 2.0) [Data set]. *NERC EDS UK Polar Data Centre* https://doi.org/10.5285/0313090c-373e-4e2e-97f2-6cd0d4138e75 (2022).
199. Thomas, E. R. & Abram, N. J. Ice core reconstruction of sea ice change in the Amundsen-Ross Seas since 1702 A.D. *Geophys. Res. Lett.* **43**, 5309–5317 (2016).
200. Thomas, E. R. Amundsen-Ross sea ice reconstruction based on data from the Ferrigno ice core (F10), Bryan Coast, West Antarctica (version none) [Data set]. *Natural Environment Research Council* https://doi.org/10.5285/1f44795b-e596-433c-b69f-caf674880daa (2017).
201. Abram, N. J. et al. Ice core evidence for a 20th century decline of sea ice in the Bellingshausen Sea, Antarctica. *J. Geophys. Res. Atmos.* https://doi.org/10.1029/2010JD014644 (2010).
202. Curran, M. A. J., van Ommen, T. D., Morgan, V. I., Phillips, K. L. & Palmer, A. S. Ice core evidence for Antarctic Sea Ice decline since the 1950s. *Science* **302**, 1203–1206 (2003).
203. Curran, M. & van Ommen, T. 150 year MSA sea ice proxy record from Law Dome, Antarctica, (version 1) [Data Set]. *Australian Antarctic Data Centre* https://doi.org/10.26179/5bf4b43fd4f45 (2011).
204. Morlighem, M. et al. Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nat. Geosci.* **13**, 132–137 (2020).
205. DeConto, R. M. et al. The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593**, 83–89 (2021).
206. Li, L., Aitken, A. R. A., Lindsay, M. D. & Kulessa, B. Sedimentary basins reduce stability of Antarctic ice streams through groundwater feedbacks. *Nat. Geosci.* **15**, 645–650 (2022).
207. Sun, Y., Wang, Y., Zhai, Z. & Zhou, M. Changes in the Antarctic's summer surface albedo, observed by satellite since 1982 and associated with sea ice anomalies. *Remote Sens.* **15**, 4940 (2023).
208. van Wessem, J. M., van den Broeke, M. R., Wouters, B. & Lhermitte, S. Variable temperature thresholds of melt pond formation on Antarctic ice shelves. *Nat. Clim. Change* **13**, 161–166 (2023).
209. Shepherd, A. et al. Trends in Antarctic Ice Sheet elevation and mass. *Geophys. Res. Lett.* **46**, 8174–8183 (2019).
210. Rignot, E., Mouginot, J. & Scheuchl, B. Ice flow of the Antarctic Ice Sheet. *Science* **333**, 1427–1430 (2011).
211. Ivins, E. R. et al. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *J. Geophys. Res. Solid Earth* **118**, 3126–3141 (2013).
212. Schmidt, A. E. & Ballard, G. Significant chick loss after early fast ice breakup at a high-latitude emperor penguin colony. *Antarct. Sci.* **32**, 180–185 (2020).
213. Fretwell, P. Four unreported emperor penguin colonies discovered by satellite. *Antarct. Sci.* **36**, 277–279 (2024).
214. Pawlowicz, R. M_Map: a mapping package for MATLAB version 1.4 m (Computer Software), https://github.com/g2e/m_map (2020).
215. Greene, C. A. et al. The climate data toolbox for MATLAB. *Geochem. Geophys. Geosyst.* **20**, 3774–3781 (2019).
216. Stål, T. & Reading, A. M. A grid for multidimensional and multivariate spatial representation and data processing. *J. Open Res. Softw.* **8**, 2 (2020).
217. Abram, N. J., Wolff, E. W. & Curran, M. A. J. A review of sea ice proxy information from polar ice cores. *Quat. Sci. Rev.* **79**, 168–183 (2013).
218. Cotté, C. & Guinet, C. Historical whaling records reveal major regional retreat of Antarctic sea ice. *Deep Sea Res.* **54**, 243–252 (2007).
219. de la Mare, W. K. Changes in Antarctic sea-ice extent from direct historical observations and whaling records. *Clim. Change* **92**, 461–493 (2009).

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Author contributions N.J.A. led the conceptualization and project management. N.J.A. and A.P. led the sea-ice team that also included P.H. and E.W.D.; M.H.E. led the ocean circulation team that also included A.P., J.B.-S. and T.J.W.; F.S.M. led the ice sheets team that also included T.S., A.M.R., A.M., R.R., R.W. and A.K.K.; J.M.S. and D.M.B. led the biology team that also included B.W., P.W.B., S.L.C. and S.A.R.; N.J.A. and T.R.V. led the implications section that also included P.H.; N.J.A., A.P., T.R.V., T.S. and B.W. produced the figures. All authors contributed to writing and reviewing the text and figures.

Competing interests S.L.C. is an Honorary Life Member of the Scientific Committee on Antarctic Research.

Additional information

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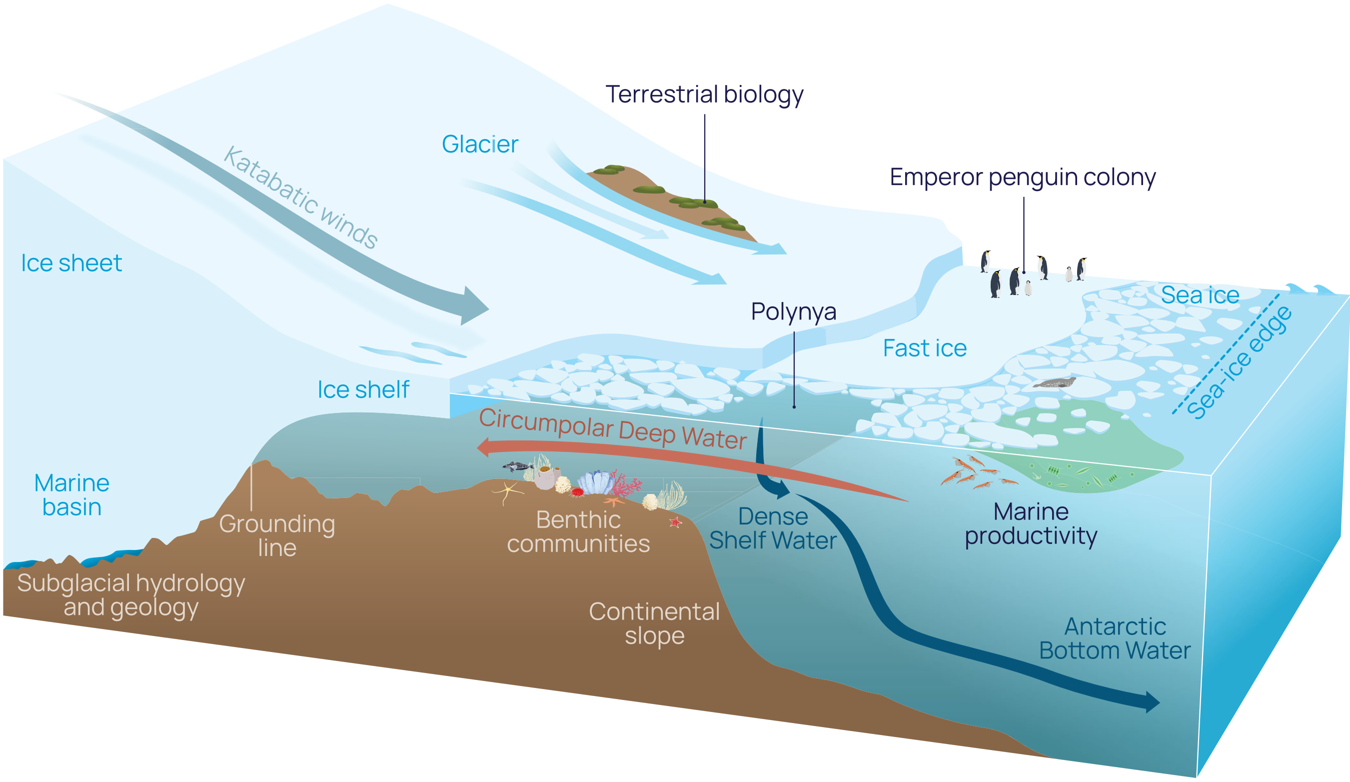
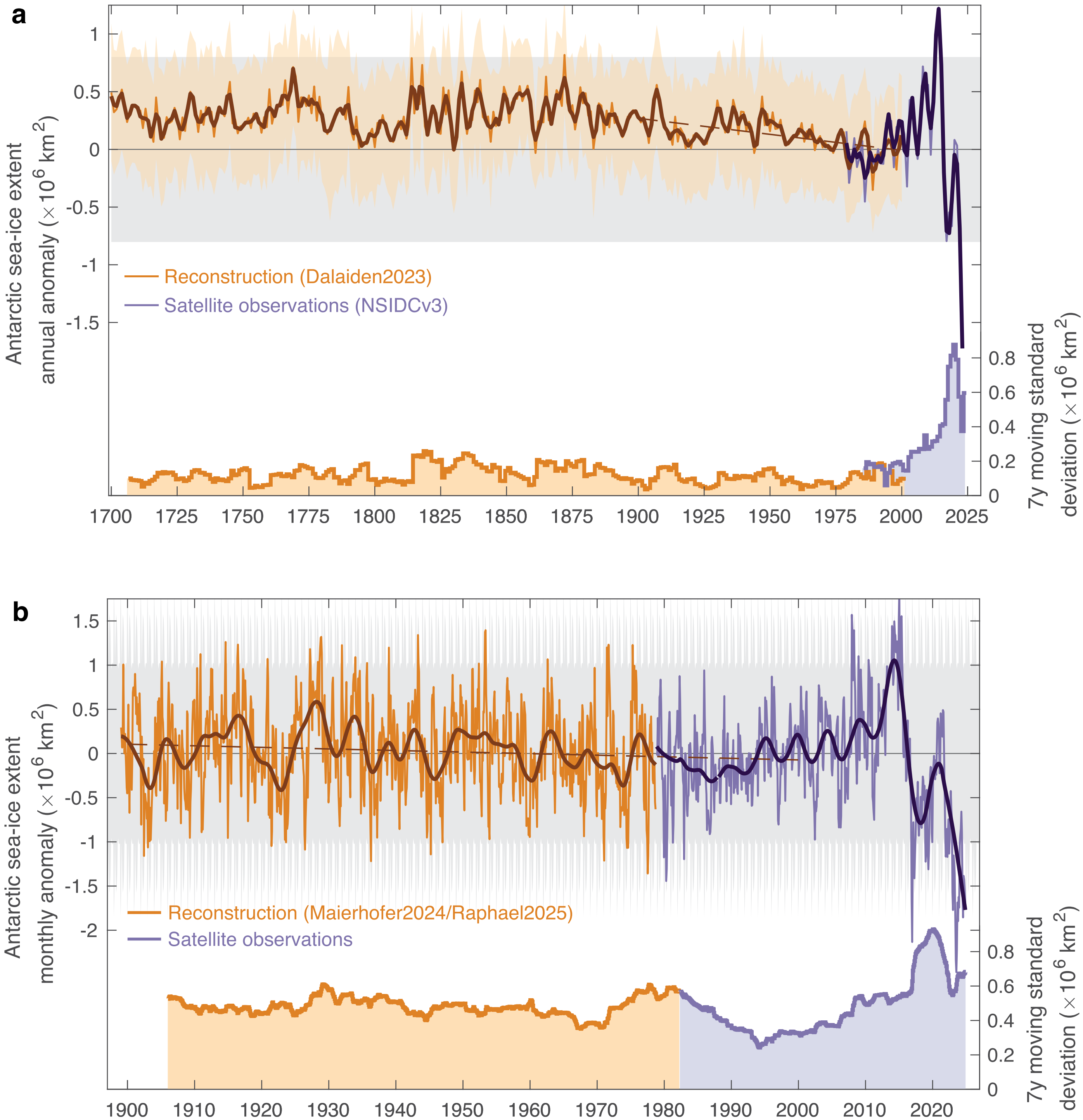
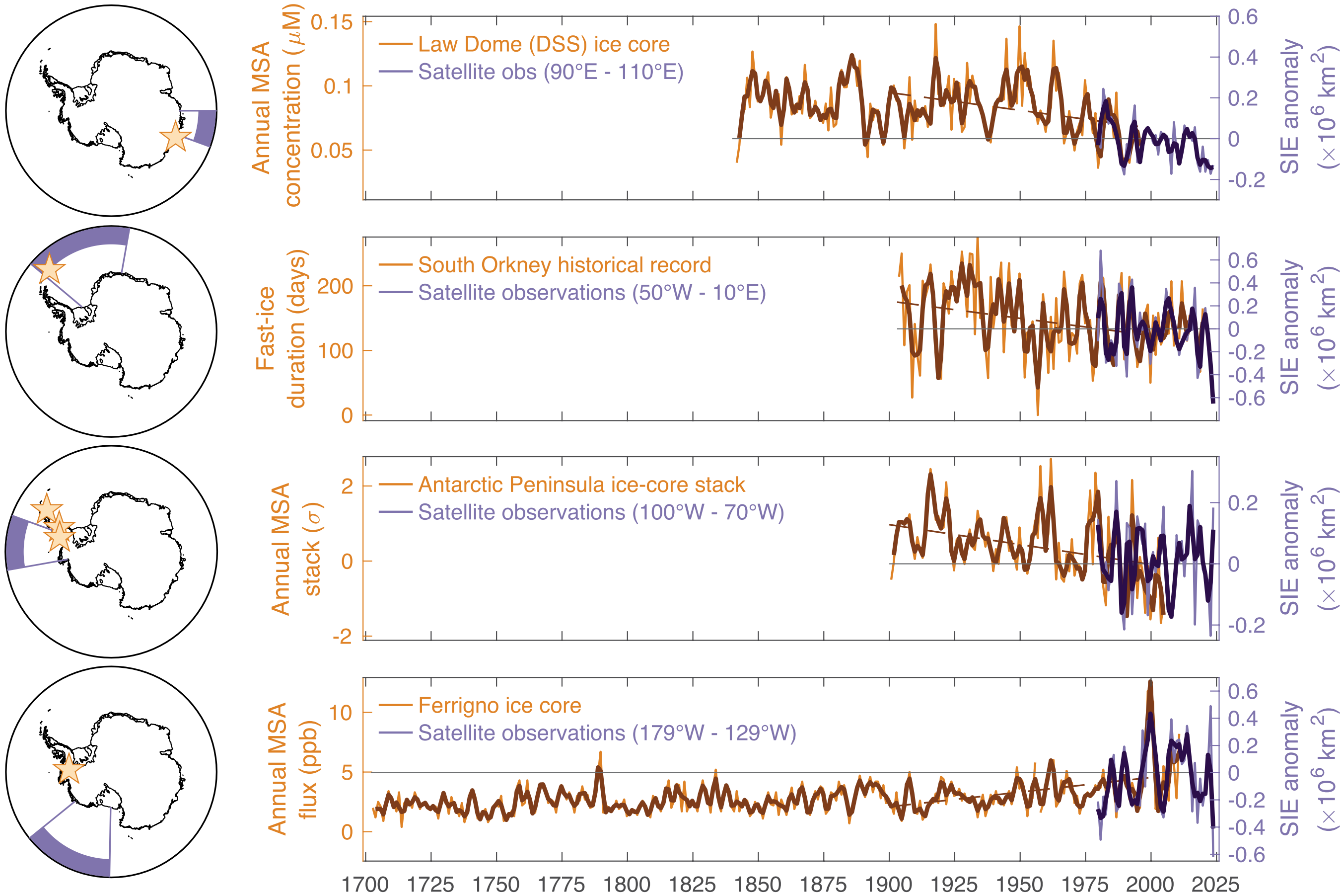


Extended Data Fig. 1 | Schematic of key components of the Antarctic environment that are discussed in this review.

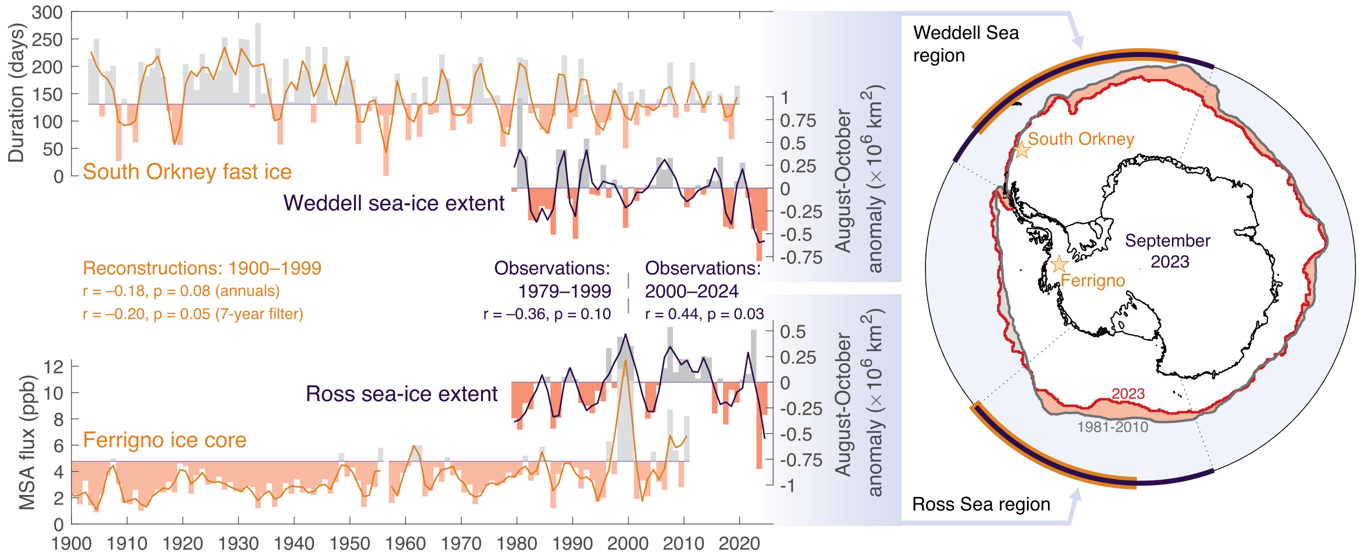


Extended Data Fig. 2 | See next page for caption.

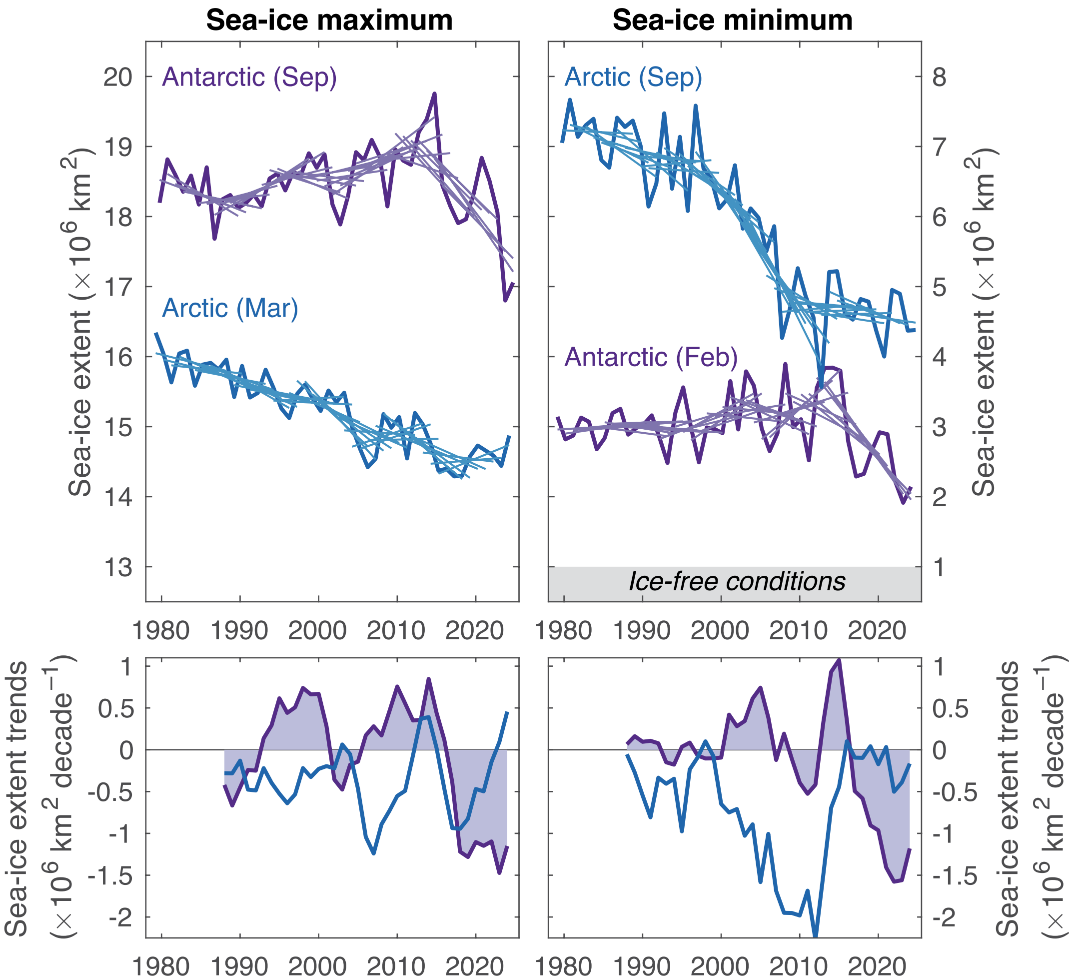
Extended Data Fig. 2 | Paleoclimate and historical context for recent Antarctic sea-ice change. a, Antarctic sea-ice extent anomaly at annual resolution for satellite observations (purple)[192] and a proxy assimilation-based reconstruction (orange) spanning 1700–2000 that is derived from assimilation of Southern Hemisphere ice-core and tree-ring paleoclimate records with coupled climate model simulations[22] (Methods). This reconstruction is fully independent of the Fogt reconstruction (Fig. 1d,e) in its input data and methodology, and is also not trained to the observational sea-ice record. Thick curves show a 7-year loess filter of the ensemble mean annual reconstruction, orange shading shows the standard deviation of the reconstruction ensemble, and dashed brown line shows the 20th century linear trend (0.28 ± 0.04 million km^2 decline from 1900 to 1999) of the sea-ice reconstruction. Both datasets are plotted relative to their 1981–2000 mean (note the reduced reference interval to calculate anomalies due to the reconstruction ending in 2000), and grey shading shows the ±3σ range of observed annual sea-ice extent anomalies over 1981–2010. Observed Antarctic annual sea-ice extent anomalies exceed −6σ relative to 1981–2010 climatology during 2023. Lower section shows the moving 7-year standard deviation of the annual sea-ice observations (purple) and reconstruction (orange), plotted at the final year of each 7-year window. **b**, as in a but for a Bayesian reconstruction of monthly sea-ice extent anomalies from 1899–1978 based on historical climate observations (orange)[24,25]. Plot shows the 1st of the 2,500 plausible reconstruction members, and all reconstruction members are considered equally likely. Across the 2,392,500 reconstructed months (957 months for 2,500 reconstruction members), only 0.52% of months have anomalies below −3σ, only 0.0016% of months have anomalies below −6σ, and only 1 month has an anomaly below the −7.3σ level which was observed in July 2023. The 20th century linear trend of the 1st ensemble member is a 0.18 ± 0.05 million km^2 decline in Antarctic sea-ice extent from 1900–1999, and the median (5^{th} to 95^{th} percentile range) of 20^{th} century trends across all ensemble members is a decline of 0.47 (0.01 to 0.92) million km^2.



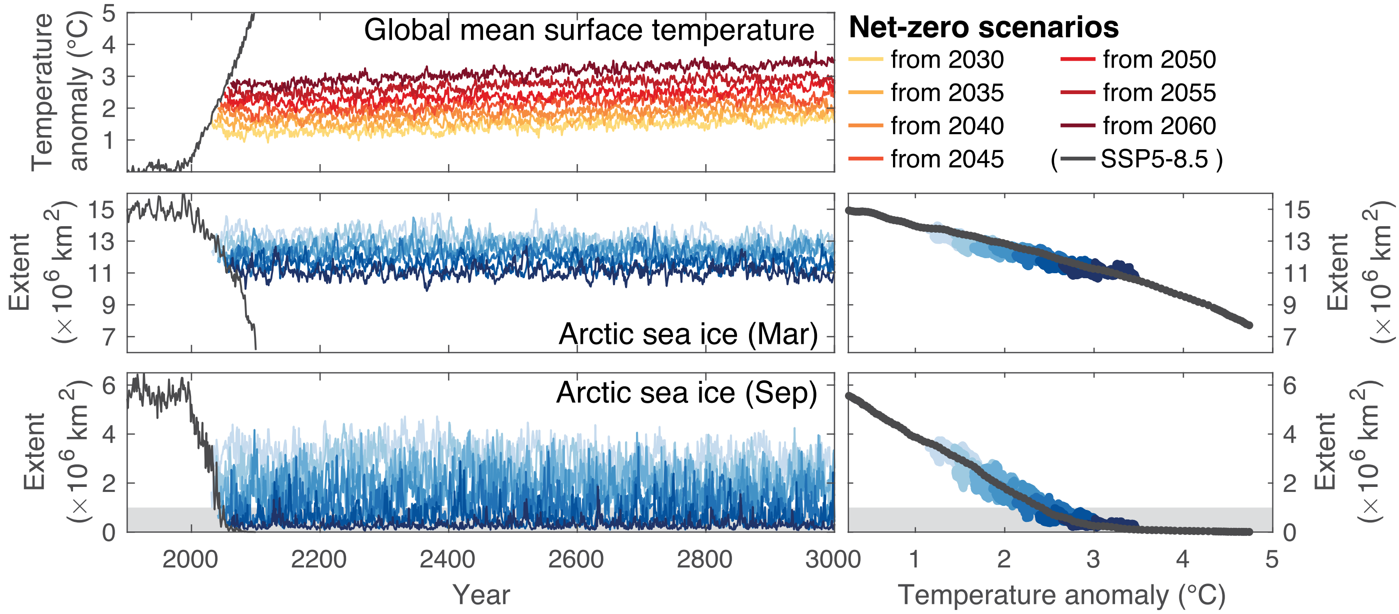
Extended Data Fig. 3 | Regional reconstructions of Antarctic sea-ice maximum changes. Annual ice-core chemistry records[199,201,202] and historical observations[197] (orange) that have been shown to be indicative of August-October sea-ice extent (purple) for different regions around Antarctica (Methods). Left column: Maps show the location of the proxy record (orange stars) and the longitudes over which each proxy represents sea-ice extent (purple arcs). Right column: Thick lines show 7-year loess filters of the annual data and dashed brown lines show 20th century linear trends on the reconstructions. Reconstruction regions are based on assessments of statistically significant process-based relationships[199,201] and scaling of the y-axes is based on the geometric mean regression between the proxy/historical and observed datasets. These regional reconstructions have been used to estimate that the August–October maximum in sea-ice extent contracted southwards in the Bellingshausen, Weddell and Indian Ocean sectors by around 0.5° to 1.2° (or around 56 to 133 km) during the 20th century[201,217]. The timing of sea-ice decline is not consistent across these sectors, emphasising the regional variability of Antarctic sea ice in addition to the long-term circum-Antarctic trends. Widespread Antarctic summer sea-ice decline during the 20th century, with regional variability, has also been inferred based on shipping charts and whaling catch records[218,219]. Notable regional variability is also evident in the Ross Sea sector, where the Ferrigno ice core estimates a 1° northward expansion of winter sea-ice extent during the 20th Century[199] (Extended Data Fig. 4).



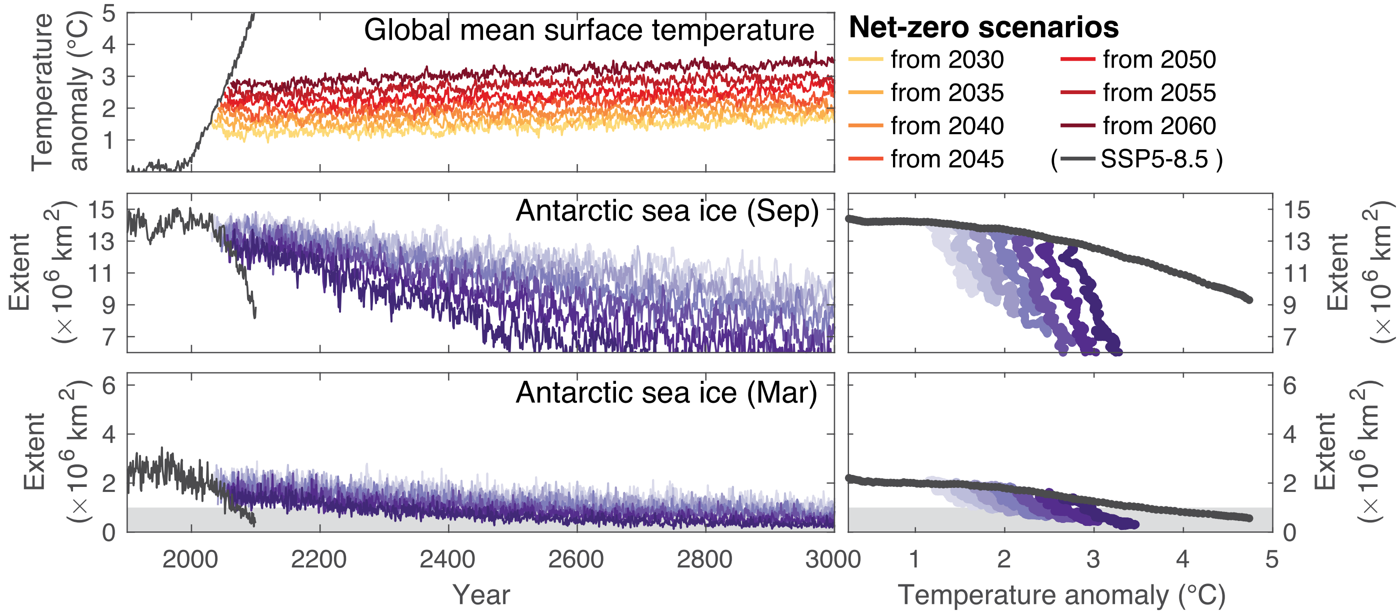
Extended Data Fig. 4 | Changing regional Antarctic sea-ice variability. Comparison of observed maximum (August-October) sea-ice extent in the Weddell (60°W–20°E) and Ross Sea (160°E–130°W) sectors, alongside 20th century indicators of August–October sea-ice extent derived from the South Orkney fast-ice duration observations[197] and the Ferrigno ice-core methanesulphonic acid (MSA) record[199] (Methods). Bar direction/colour is plotted relative to the 1981–2010 mean of each record, and lines show a 7-year loess filter of the annual data. Correlation values give details of the changing relationship between sea-ice variability in the Weddell and Ross regions between the 20th and 21st centuries. Map shows sea-ice extent in September 2023 (red) compared to the 1981–2010 September median (grey). Red (grey) shading indicates regions with sea-ice extent less (more) than the 1981–2010 median. Purple arcs indicate the longitude ranges of the Weddell and Ross sea regions in the satellite sea-ice data[192]. Orange arcs indicate the longitude ranges where the Ferrigno ice core and South Orkney observations (stars) have a statistically significant relationship with August-October sea-ice extent[199,201]. The pre-satellite data add evidence to the unusual recent increase in coherence of Antarctic sea-ice anomalies between regions[16,20]. Ice core and historical records confirm that opposing August–October sea-ice extent variability ($r = -0.18$, $p = 0.08$ for annual reconstructions) and trends ($r = -0.20$, $p = 0.05$ for 7 y filtered reconstructions) were a persistent characteristic between the Weddell and Ross sectors throughout the 20th century[199]. The anticorrelation between these regional reconstructions over 1900–1999 is also evident in satellite observations of August–October sea-ice anomalies between the Weddell and Ross sea regions ($r = -0.36$, $p = 0.10$, 1979–1999). These compensating regional sea-ice anomalies have diminished through the satellite era[16], and during the 21st century a significant positive relationship has now developed between August–October sea ice in the Weddell and Ross seas ($r = 0.44$, $p = 0.03$, 2000–2024). This change in regional behaviour may reflect the increasing importance of widespread ocean warming on recent Antarctic sea-ice declines this century[19,20] compared to the atmospheric processes that dominated regional variability in Antarctic sea ice during the 20th century[11,20,199].



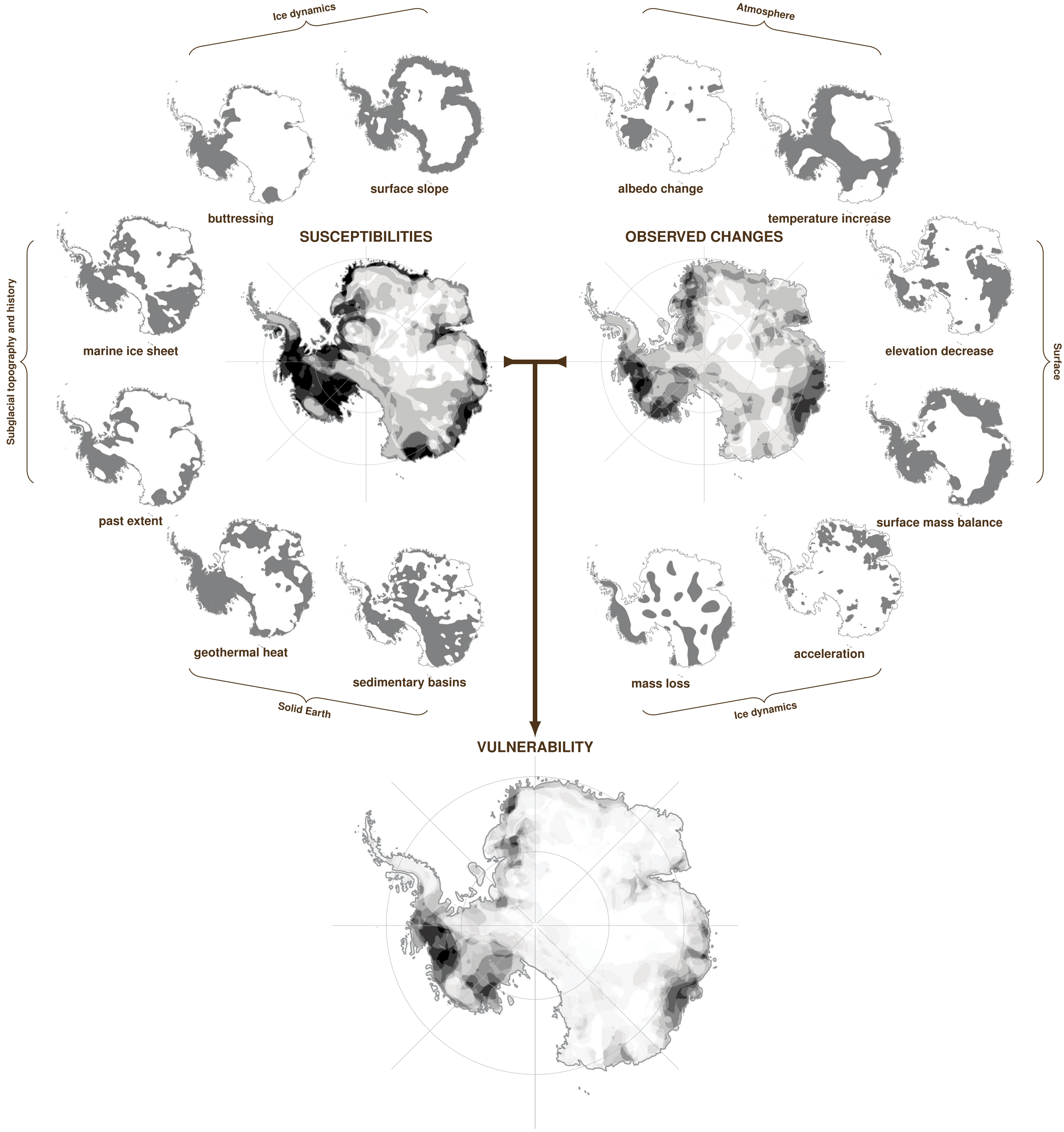
Extended Data Fig. 5 | Comparison of decadal trends in Antarctic and Arctic sea-ice extent. Satellite record of annual maximum (left) and minimum (right) sea-ice extent for Antarctica (purple) and the Arctic (blue), as in Fig. 2. Thin lines (upper panels) indicate linear decadal trends calculated across the length of the satellite record, which are also plotted as moving decadal trends (lower panels) with respect to the end-year of the decadal windows. The decadal loss trends in the Antarctic sea-ice maximum (left) for windows ending from 2018 or later are more abrupt and persistent than decadal trends in the Arctic sea-ice maximum across the satellite era. For the sea-ice minimum (right), persistent decadal-scale loss has occurred in the Antarctic for all decades ending from 2017 or later, and ice loss during the decades ending in 2022 and 2023 was more abrupt than any decadal loss trends in the Antarctic sea-ice maximum during the satellite-era. However, recent decadal declines in the Antarctic sea-ice minimum are not as abrupt as the rate of ice loss for the Arctic sea-ice minimum that occurred in the decades ending between 2007 and 2012.



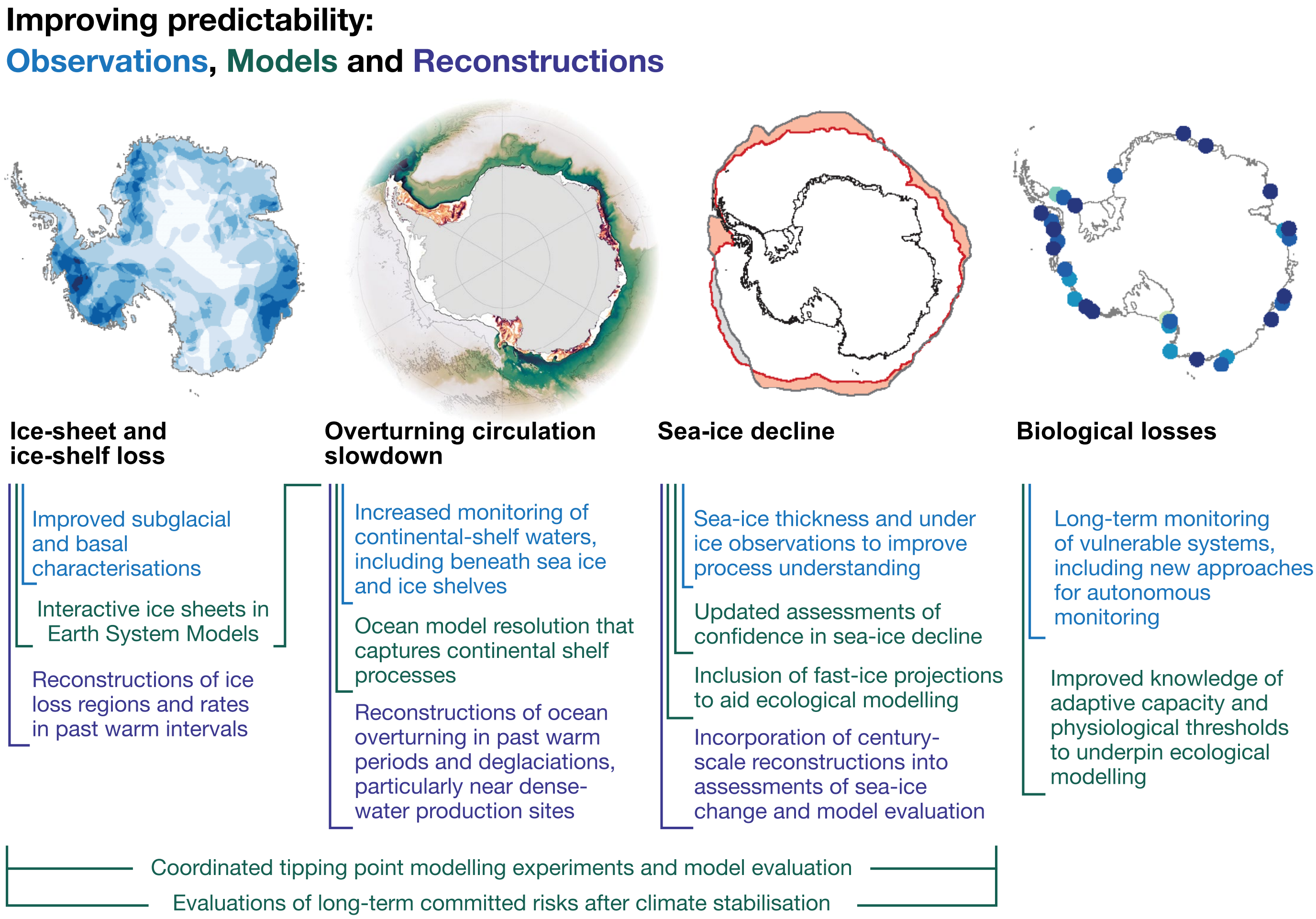
Extended Data Fig. 6 | Arctic sea ice in climate stabilisation scenarios. Left column: Evolution of global mean surface temperature (yellow-red curves) and Arctic sea-ice extent (light to dark blue curves) under net-zero emission scenarios run for 1000 years after branching from a very high emissions scenario (SSP5-8.5; black curves). Net-zero scenarios were branched every 5 years from 2030 to 2060, and are plotted in progressively darker shades. Right column: Relationship between global mean surface temperature and sea-ice extent climatology (30-year moving averages) in climate stabilisation scenarios (blue curves) and SSP5-8.5 (black curves). Grey shading in the lower row indicates ice-free conditions as defined by sea-ice extent less than 1 million km^2. Arctic sea-ice maximum (March) and minima (September) show strong linearity with global mean surface temperature and no long-term commitments for sea-ice decline after net-zero emissions are achieved, indicating that Arctic sea ice does not display tipping-element behaviour. Simulation data from ACCESS-ESM1.5, as described in ref. 34 (Methods).



Extended Data Fig. 7 | Antarctic sea ice in climate stabilisation scenarios. Left column: Evolution of global mean surface temperature (yellow-red curves) and Antarctic sea-ice extent (light to dark purple curves) under net-zero emission scenarios run for 1000 years after branching from a very high emissions scenario (SSP5-8.5; black curves). Net-zero scenarios were branched every 5 years from 2030 to 2060, and are plotted in progressively darker shades. Right column: Relationship between global mean surface temperature and sea-ice extent climatology (30-year moving averages) in climate stabilisation scenarios (purple curves) and SSP5-8.5 (black curves). Grey shading in the lower row indicates ice-free conditions as defined by sea-ice extent less than 1 million km^2. Antarctic sea-ice maximum (September) and minimum (March) show century to millennia-scale commitments for irreversible sea-ice loss after net-zero emissions are achieved suggestive of self-perpetuating tipping behaviour, in contrast to Arctic sea-ice behaviour (Extended Data Fig. 6). Simulation data from ACCESS-ESM1.5, as described in ref. 34 (Methods).



Extended Data Fig. 8 | Compilation of the datasets of ice-sheet susceptibilities and observed changes that are shown in Fig. 4. Left: Threshold maps used to perform a qualitative assessment of areas of susceptibility, grouped by area of impact: surface slope (BedMachine)[204]; buttressing (PISM)[116]; marine ice sheet (BedMachine)[204]; Pliocene reconstruction[205]; geothermal heat above median[147]; Sedimentary Basin above median likelihood[206]. Right: Threshold maps of various aspects of observed changes: albedo change above median amplitude[207]; air temperature (RACMO)[208]; elevation lowering (Antarctic Climate Change Initiative)[209]; where surface mass balance trend (2022-1979) is negative (RACMO2.3p2)[208]; ice flow acceleration (MEaSUREs v2)[101,210]; mass loss (GMB; TUD 2024)[211]. Lower: Indicative vulnerability derived from the product of the aggregated fields of susceptibilities and observed changes (Methods).



Extended Data Fig. 9 | Priorities for improving the predictability of abrupt changes in the Antarctic environment. These include new or improved observations (blue), targeted development and application of reconstructions (purple), and incorporation of key Antarctic processes in models and coordinated evaluation of model simulations (green). Base images used to represent each Antarctic system are derived from Figs. 1, 3, 4 and 5.