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Rapid decline in Antarctic sea ice in recent years hints at future change

Clare Eayrs[1]✉, Xichen Li[2,3], Marilyn N. Raphael[4] and David M. Holland[1,5]

Following years of record highs, an unexpected and precipitous reduction in Antarctic sea-ice extent started in 2016. This decline, lasting three years, was the most pronounced of the satellite era, equivalent to 30 years of sea-ice loss in the Arctic. Here, we synthesize recent work showing this sea-ice reduction probably resulted from the interaction of a decades-long ocean warming trend and an early spring southward advection of atmospheric heat, with an exceptional weakening of the Southern Hemisphere mid-latitude westerlies in late spring. We discuss what this event reveals about the underlying atmospheric and oceanic dynamical processes that control sea ice in the region and the ways in which shifting climate variability and remote forcings, especially from the tropics, influence these processes. Knowledge gaps show that further work is needed to improve future projections of changes in one of the largest seasonal phenomena on the planet.

Antarctic sea ice is very seasonal and each year some 15 million km^2 of ice grows and melts. Such extensive change in sea-ice cover has huge implications for the exchange of energy, momentum and gases between the atmosphere and the ocean. Sea-ice variability occurs on a wide range of timescales, but much current research focuses on seasonal and interannual variability due to the insufficient length of the present 40-year satellite record to assess longer-term trends[1]. There is large variability in the amount of sea ice that forms and melts each year (Fig. 1a), but unlike Arctic sea ice, which has declined precipitously over the satellite record[2], total Antarctic sea ice has shown a slight, overall positive linear trend, one that nonetheless masks large regional variability[3] (Fig. 1c). Substantial natural interannual variability may partly explain this ambiguity[4], although this raises the question of why Arctic sea ice is not similarly affected. The geographies are, of course, vastly unalike, which contributes to large differences in the oceanic and atmospheric circulations[2]. Regional surface winds[5] and remote tropical climate anomalies[6–9] have been shown to play a role in driving the slight, overall positive linear trend. In particular, applying realistic wind forcing and sea-surface temperatures (SSTs) leads to improved skill in reproducing the observed sea-ice trends[10].

Antarctic sea ice dropped rapidly from a record high in 2014 to a record low in 2017[11]. This dramatic, unanticipated loss in sea-ice cover equalled the 30-year observed decrease in Arctic sea ice. In this Perspective, we describe the factors leading to the recent precipitous decline and the insights that can be drawn from this about the current and future drivers of trends in Antarctic sea ice. We outline current knowledge gaps and highlight research directions that can potentially improve future understanding of change to the surface cover in the Southern Ocean.

The recent rapid decrease in Antarctic sea-ice cover

The increase in Antarctic sea ice between 2000 and 2014 accelerated to almost five times the rate observed between 1979 and 1999[12], culminating in a record high annual mean sea-ice extent (SIE) of 12.8 million km^2 in 2014[11]. What happened next was completely unexpected. Over just three years, the annual mean SIE fell to a record low of nearly 2.1 million km^2 below the long-term mean (Fig. 1a). Such a rapid drop is unprecedented in the 40-year satellite record and stands in stark contrast to the overall trend[11]. Whether or not the recent decline has had an appreciable effect on the overall positive linear trend depends on the time period taken and how the statistics are treated. Regional changes during the recent decline (Fig. 1d) were almost opposite to the long-term trend (Fig. 1c). Nearly all regions experienced dramatic sea-ice loss, particularly in the Weddell Sea. Part of the western Ross Sea and the Indian Ocean were the only places that did not experience anomalously low sea-ice concentrations (SICs)[11].

Changes in the timing (phase) of sea-ice advance and retreat might be governing contemporary trends in Antarctic sea ice[13]. The anomalous decay of sea ice in 2016 was associated largely with a change of phase rather than amplitude[6], with an earlier (August rather than at the end of September) and faster than usual seasonal retreat. The loss of sea ice early in the spring allows more solar radiation to be absorbed by the ocean, which can hasten the melt. The subsequently longer ice-free season leads to increased shortwave absorption in the ocean during summer months that delays sea-ice formation the following autumn[14].

Key mechanisms influencing Antarctic sea-ice cover

A number of key thermodynamical and dynamical processes control sea-ice cover and its variability (Fig. 2). The lower atmosphere plays a thermodynamical role through the advection of warm/cold air and dynamically through wind drift. The upper ocean plays a role through heat transfer between the lower atmosphere and the deep ocean[15]. The larger-scale atmospheric circulation exerts control on the surface wind speed and direction, and thereby moderates these thermodynamical and dynamical processes.

Natural climate fluctuations modify the westerly winds that encircle Antarctica via a circulation pattern known as the Southern Annular Mode (SAM) that periodically strengthens (SAM$^+$) or weakens (SAM$^-$) these winds. A two-timescale response to the

[1]Center for Global Sea Level Change, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates. [2]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China. [3]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Hangzhou, China. [4]UCLA Department of Geography, University of California, Los Angeles, CA, USA. [5]Courant Institute of Mathematical Sciences, New York University, New York, NY, USA. ✉e-mail: clare.eayrs@nyu.edu

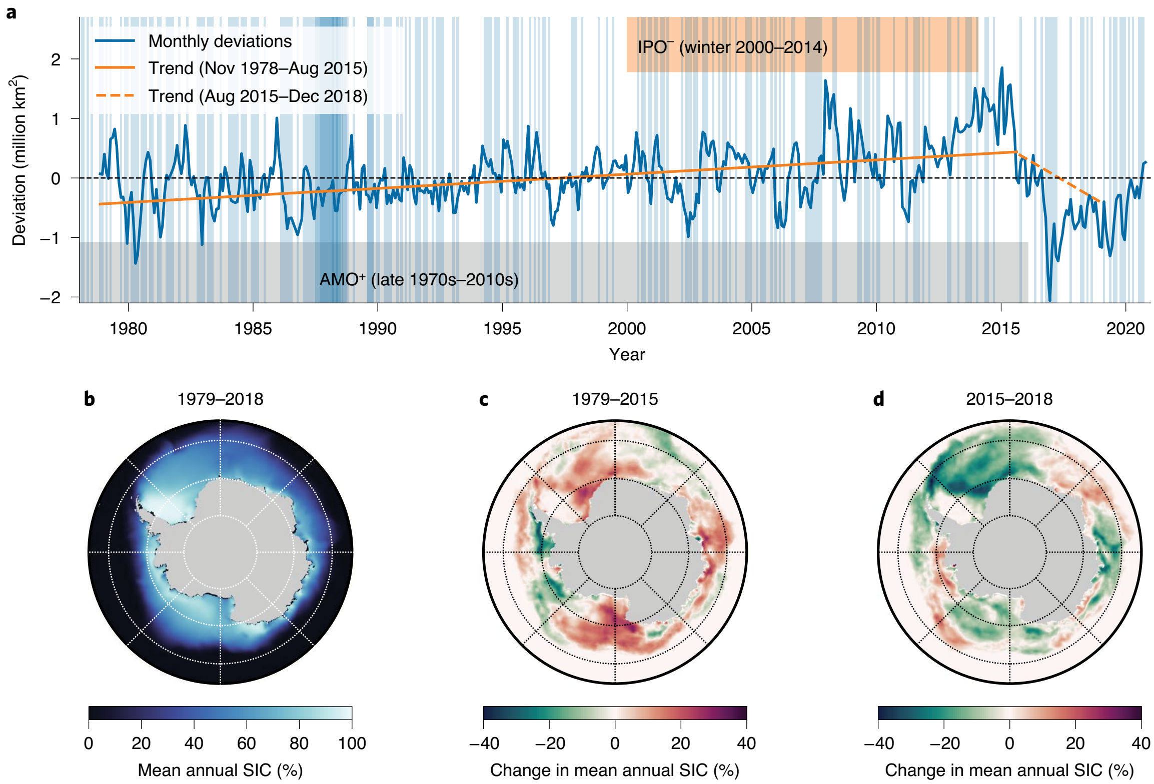

Fig. 1 | Variability in SIE and SIC derived from passive microwave remote sensing. a, Monthly mean SIE anomalies since 1979 with respect to the 1979–2018 climatology (blue line); trend lines (orange; dashed orange) calculated through the monthly anomalies[53]. Orange shading shows the IPO⁻ and grey shading shows the AMO⁺. Blue shading shows months with weakened westerlies (SAM⁻ (ref. [55])). **b**, Mean annual SIC 1979–2018. **c**, Mean annual SIC changes from 1979 to 2015. **d**, Mean annual SIC changes from 2015 to 2018[54].

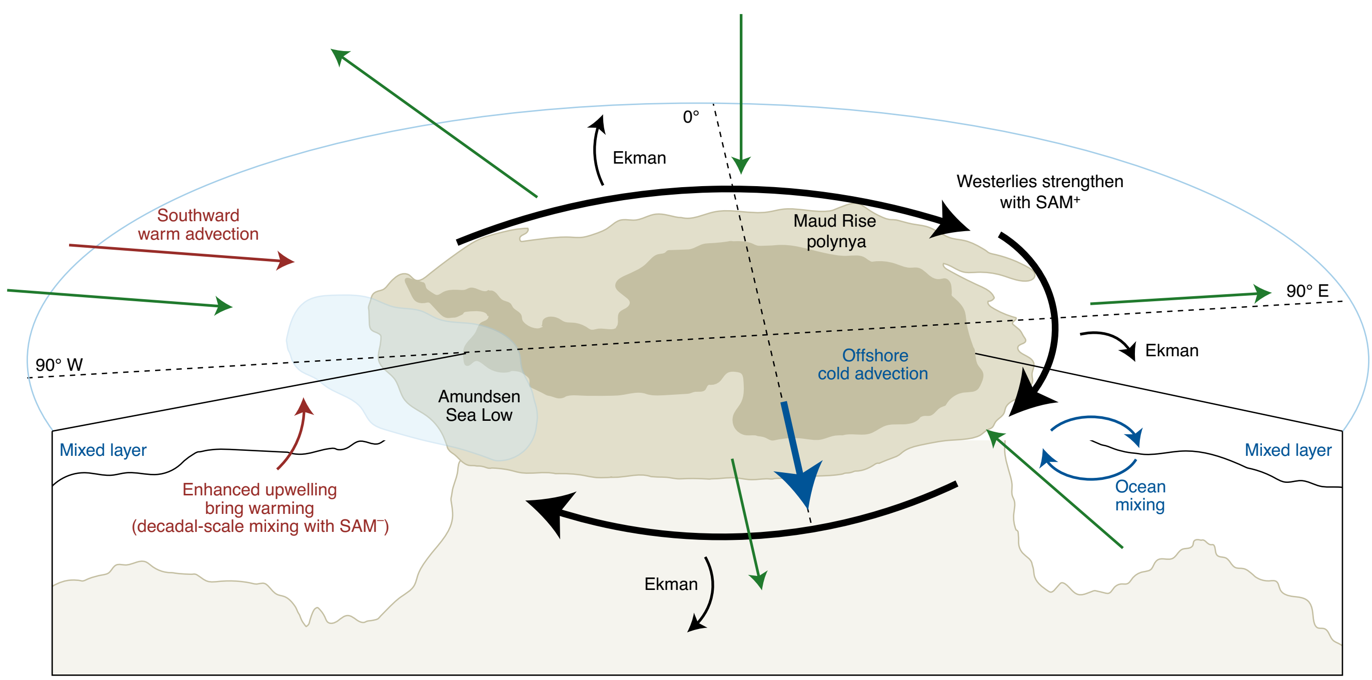

Fig. 2 | Mechanisms influencing sea-ice cover and its variability. SAM⁺ strengthens the westerlies that circumnavigate Antarctica (black arrows) forcing the advection of cold, surface mixed-layer waters northwards through the Ekman effect (small grey arrows). On seasonal and interannual timescales, this can lead to increased sea-ice cover. Anomalous meridional air flow (green arrows) associated with a zonal-wavenumber-three pattern can bring warm air southwards (for example, large red arrow) or blow cold air northwards (for example, large blue arrow). On decadal timescales, strengthened westerlies upwell warm, deep waters to the surface (small red arrow), leading to decreased sea-ice cover.

strengthened westerlies has opposing effects on sea-ice cover[12,16–18]. On interannual and shorter timescales, strengthened westerlies drive cooling and sea-ice expansion by advecting cold, surface mixed-layer waters northwards by the Ekman effect. On decadal to multidecadal timescales, this enhanced northward transport is thought to drive upwelling of warm, deep waters from below the mixed layer and lead to sea-ice reduction.

SAM anomalies are zonally symmetric by definition, but there is also a non-annular component[7] to the wind variability pattern, especially in the Amundsen Sea Low (ASL) region. The ASL, located in the South Pacific sector of the Southern Ocean (Fig. 2), is the deepest of three climatological low-pressure centres observed around Antarctica[19]. When in its average location[20], southerly air flow on the western flank of the ASL pulls cold air from the continent over the Ross Sea, expanding the sea-ice cover to the north and simultaneously moving ice away from the coast, exposing open water at the coastline, which then refreezes. The opposite happens on the eastern flank of the ASL, where warm northerly flow acts to limit SIE in the Amundsen and Bellingshausen seas[21]. Changes in intensity of the ASL affect the strength of these responses.

The ASL is part of a larger zonal-wavenumber-three circulation pattern that affects the surface winds across all of the Southern Ocean, a quasi-stationary asymmetric pattern of three ridges that generally lie south of the southern continents and three interspersed troughs. This zonal pattern has considerable impacts on meridional heat transport and therefore Antarctic sea-ice cover[22–24]. A strong zonal-wavenumber-three pattern indicates strong meridional flow[25], with an alternating pattern of cold (northward) and warm (southward) flow encircling the Antarctic continent.

The SAM and the ASL are influenced by larger-scale atmospheric teleconnections, resulting from changes in surface fluxes in tropical regions. The El Niño/Southern Oscillation and its strongly co-varying Indian Ocean neighbour, the Indian Ocean Dipole, modify SSTs in the tropical Pacific and Indian oceans. A warmer ocean surface triggers atmospheric convection that sets up a stationary Rossby wave train. The wave train increases the surface pressure over the Amundsen Sea and shifts the polar jet stream northwards. There is compelling evidence that multidecadal sea-ice trends are driven by the decadal variability of tropical SSTs[9,26].

Two key climate cycles that regulate tropical SSTs are the Interdecadal Pacific Oscillation (IPO) and the Atlantic Multidecadal Oscillation (AMO). The IPO is an index representing how the western Pacific temperatures swing back and forth between warm (IPO^+) and cool (IPO^-) phases every few decades, whereas the AMO represents an analogous phenomenon of SST in the North Atlantic Ocean. Changes in the tropical oceans have been shown to strengthen the westerly winds of the Southern Ocean via both the AMO[8,26–29] and the IPO[9]. The IPO affects Antarctic atmospheric circulation through Rossby wave trains, with anomalies persisting for decades[9,30]. The positive phase of the IPO favours weakened westerlies and an anomalous high pressure in the Amundsen and Bellingshausen seas. This disturbance originates from the central equatorial Pacific and propagates southwards through Rossby waves leading to changes of the ASL[31]. The negative (positive) phase of the IPO may strengthen (weaken) the westerlies and deepen (shallow) the ASL. In an analogous fashion, SST[32] variability in the north and tropical Atlantic generates a stationary Rossby wave train that propagates to the Southern Ocean along the subtropical jet stream, and ultimately influences the atmospheric circulation around Antarctica. The positive (negative) phase of the AMO may intensify (weaken) the westerlies and deepen (shallow) the ASL[27,29]. Both the positive phase of the AMO since the late 1970s and the negative phase of the IPO since the early 2000s deepened the ASL and contributed to an intensification of the SAM, which favoured the observed long-term increase of the total sea-ice cover around the Antarctic before 2015 (Fig. 1a). In the next section, we discuss the contribution of climate variability to the recent rapid decline in Antarctic sea ice.

A perfect storm

Decadal scale warming of the ocean subsurface from strengthened westerlies, caused by IPO^- (2000–2014; Fig. 1a), warmed subsurface waters over the preceding years, potentially setting the stage for melting sea ice[12]. Through August to October 2016, a persistently positive zonal-wavenumber-three pattern produced strong southward atmospheric heat advection[32] in the Indian Ocean, and Ross and Bellingshausen sea sectors[23]. A record deep ASL in September generated strong northwesterly winds across the Amundsen–Bellingshausen and Weddell seas that led to below-average sea-ice retreat in these regions[23]. Although sea-ice cover was low, nothing extraordinary had happened up to this point. Then in November 2016, an unexpected but near-record SAM^- (refs. [23,24]) brought about intense easterly wind anomalies[33] that pushed sea ice towards the continent and created the exceptional reduction in sea ice.

There is low confidence regarding which drivers set up these anomalous winds as there are numerous explanations offered. The zonal-wave-number three pattern in early spring has been related to the 2015/2016 El Niño that weakened the ASL, leading to a dipole pattern of SSTs with warm waters in the eastern Ross, Amundsen and Bellingshausen seas[24]. However, it has also been linked to record high and low pressures in the Ross and Amundsen seas, respectively[23], and to record-strength negative Indian Ocean Dipole[33] or precipitation anomalies[12] in the tropical eastern Indian and western Pacific oceans. Likewise, the record SAM^- (refs. [23,32]) has been linked to the recovery of stratospheric ozone[33], a combination of the record tropical Indian and Pacific Ocean heating anomalies followed by an unusually early breakdown of the stratospheric polar vortex[33], the change to IPO^+ and negative AMO^- (refs. [8,12]), and to internal climate variability[24].

Neither is there consensus on whether deep ocean heat was brought to the surface in spring 2016. It is not clear what the mechanism would be to bring deep ocean heat to the surface under a weakened wind condition when melting sea ice stabilizes the water column. In the Weddell Sea, precipitation was above average in 2016[34], leading to further stabilization. One theory is that the weakened circumpolar westerlies caused southward Ekman transport of warm ocean surface waters to melt ice[12]. Another suggestion is that SSTs have been increasing since the 1970s[23], but how this relates to the anomalous SSTs experienced in spring 2016 still needs investigating.

The Weddell Sea sector made the largest contribution to the recent rapid decrease, holding 34% of the total decrease during spring 2016[35]. This negative anomaly continued through 2019–2020, with SIE across the Weddell Sea at near-record levels each summer[35]. The reappearance of the Maud Rise polynya in July 2016 and again in September 2017[34] possibly assisted by creating an extensive ice-free region that could absorb shortwave radiation early in the summer and increase ocean temperatures, facilitating sea-ice cover deterioration[35].

Future changes and research priorities

Understanding future sea-ice cover is hampered by our uncertainties in fully understanding the interacting processes and by the general sparsity of observations. Several recent reviews have highlighted important future research avenues[36–38], and we note some recent programmes and emerging techniques that can improve our understanding of future Antarctic sea-ice cover.

From the observed recovery of Antarctic sea ice (Fig. 1a), we might infer that the 2016 decline was a blip within the natural sub-decadal variability. Recent research[6] suggests that linear methods may not be the most appropriate way to define trends in Antarctic sea ice, which is inherently characterized by sub-decadal variability. The 2016 decline took many by surprise and nonlinear techniques may provide a way to better understand both past and future sea-ice trends. The 2016 decline has highlighted the need to understand processes that are interacting on a wide range of time and space scales, and new techniques are needed to monitor the atmospheric circulation over the polar region. Zonally averaged metrics such as the SAM limit our ability to incorporate the spatial asymmetry of, for example, the combined influences of IPO$^-$ and AMO$^+$. Similarly, although many studies to date have necessarily focused on monthly, seasonal and interannual timescales to connect sea-ice change to large-scale, remote forcings, information on the timing and rates of advance and retreat of the ice is disguised in these averages. Daily timescales are more appropriate to diagnose the physical contributors to sea-ice variability[6]. In particular, persistent/long-lasting in situ observations of the near-surface air temperature should feature in future observation programmes.

We continue to gain a deeper understanding of the longer-term changes as the satellite record increases in length. Creating reconstructions for the pre-satellite twentieth century provides another way to contextualize the present variability, and promising new research programmes have started to use statistical techniques to recreate seasonal sea-ice metrics based on relationships with other climate metrics and using ice-core reconstructions[39]. Given the role of large-scale climate in driving the surface wind patterns around Antarctica, these emerging techniques provide an exciting area of future research.

Owing to the understanding of recent events, there is now some insight into how the factors that contributed to these events might evolve. We might expect intensified tropical Pacific interannual variability in the future[40]. In the next few decades, the phases of the IPO and AMO may be reversed, which will probably change the regional SIE around Antarctica. However, this may be offset by the fact that the amplitudes of the IPO and the AMO are projected to decrease and their periodicity to shorten[41,42]. We might expect a shallower ASL from a faster-warming tropical eastern Pacific and slower-warming tropical eastern Indian Ocean[43]. This will lead to a dipole of sea-ice change, with decreasing sea ice in the Ross Sea and increasing sea ice in the Amundsen–Bellingshausen Sea. The two-time-step theory suggests that with strengthening westerlies, sea ice expands in the short term but in the long term it will decrease similarly to its Arctic counterpart[12]. Climate modelling also suggests that intensified westerlies will lead to increased heat storage in the Southern Ocean[43], which is conducive to a decline in sea-ice cover[12].

There is uncertainty in the role of the ocean during the recent rapid decrease and more comprehensive observations of the subsurface ocean temperature and stratification are a high priority. As a step in the right direction, the SOCCOM[44] and Deep Argo[45] programmes will greatly improve ocean reanalyses[46] and our understanding of the ocean dynamical processes in driving sea-ice evolution.

Sea-ice cover is only part of the story; volume is crucial to fully understand changes in the polar climate system. With the recently modified orbits of ICESat-2[47] and CryoSat2[48] to increase overlap, there is hope that sea-ice thickness algorithms can be refined to substantially improve estimates of Antarctic sea-ice thickness, which plays a crucial role in sea-ice formation and melting, and must be better monitored in the future. ICESat-2 and CryoSat2 are the only two satellites providing altimetry in polar regions and there is likely to be a gap of 2–5 years between decommissioning these satellites and the launch of the next polar altimeter, CRISTAL[49], planned in 2027. There is an urgent need to explore options to mitigate the potential data gap and ensure we can continue to improve our understanding of Antarctic sea-ice variability.

The recent rapid decline was largely the result of coincidental but naturally occurring variability[33], but the role of anthropogenic forcing cannot be excluded. For example, greenhouse gas forcing contributes to warming in the tropical Indian Ocean[50] and could therefore be potentially linked to the 2016 record anomalies. Observations combined with climate model simulations suggest that increased greenhouse gas forcing has caused a reversal in the Amundsen Sea shelf-break surface winds from mean easterlies in the 1920s to the near-zero mean zonal winds of today[51]. Climate projections suggest that by 2100 these shelf-break winds will have reversed to westerlies that will enhance ocean temperatures due to upwelling around the perimeter of the continent. The role of anthropogenic forcing in driving tropical teleconnections remains unclear and should be a main focus of future studies.

An exceptional weakening of the winds around Antarctica in late spring reduced sea cover to an all-time low. For now, it seems that Antarctic sea-ice cover has returned to the average climatological conditions of the modern satellite era. The recent decline demonstrates that, under certain conditions, Antarctic sea ice can be susceptible to rapid change.

Data availability

Figure 1 and its base maps were created using the Python packages Matplotlib[52] and Basemap. Sea-ice extent data in Fig. 1 are pre-calculated monthly extent values from the .csv files in version 3 from https://nsidc.org/data/g02135 that are qualitatively comparable to the quality-controlled files that end in December 2018 (ref. [53]). We have supplemented these with the near-real-time product available at the NOAA Climate Data Record of Passive Microwave Sea Ice Concentration[54], available at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, and on the NSIDC website at https://nsidc.org/data/g02202/versions/3 and https://nsidc.org/data/g10016 (near-real-time data). The SAM Index[55] was accessed at https://legacy.bas.ac.uk/met/gjma/sam.html.

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The authors declare no competing interests.

Additional information
Correspondence should be addressed to C.E.

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