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Review article

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Changes in Arctic and Antarctic sea-ice properties and processes

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Abstract

Although sea ice covers only ~9% of the world's oceans, its presence and absence greatly alter the energetic balance of Earth's climate. Owing to geographic differences, Arctic and Antarctic sea ice have different dominant properties and processes, which in turn produce different responses to natural climate variability and anthropogenic climate change. This Review surveys the changes in sea-ice properties and processes of the Arctic and Antarctic environments. The Arctic melt season has lengthened by ~7.4 days per decade during 1979–2024, alongside decreases in winter sea-ice thickness (1.6 m mean total over 1980–2023), summer surface albedo (0.03 per decade over 1979–2020) and spring snow depth (2.5 cm per decade over 1954–2024). Changes in the Antarctic are smaller than those in the Arctic owing to contrasting regional and temporal trends. From a dynamic perspective, sea-ice motion in both hemispheres has increased, by 0.63 cm s^{-1} per decade in the Arctic (1978–2024) and 0.69 cm s^{-1} per decade in the Antarctic (1982–2024), whereas trends in polynya occurrence differ by region. This Review highlights major knowledge gaps and provides recommendations for joint model-observation efforts to improve understanding of sea ice and its role in Earth's climate system.

Sections

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Introduction

Despite being a thin (<3-m mean) veneer on the ocean, sea ice is an integral component of Earth's climate system. Sea ice modulates the energy exchange between the atmosphere and ocean through complex, time-varying processes. In winter, the sea-ice cover insulates the warmer ocean from the cooler atmosphere[1], whereas during the sunlit seasons, sea ice reflects the majority of sunlight back into space[2,3]. Sea-ice growth, especially in polynyas (persistent regions of open water or thin ice surrounded by thick, contiguous sea ice)[4,5], produces bottom water masses that form the lower limb of the ocean's thermohaline circulation. Sea-ice melt drives the redistribution of freshwater and stratifies the upper ocean, which strongly influences the phenology of primary productivity and hence the polar marine ecosystem[6].

Since the late 1970s, satellite observations have recorded dramatic changes in the ice-covered oceans (Fig. 1). The extent of Arctic sea ice in September has declined by 14% per decade over 1979–2024[7]. In addition to this loss, Arctic sea ice has shifted from a perennial (multiyear) to a seasonal (first-year) regime[8–10] and continues to experience an increasingly prolonged melt season[11–13]. Current model projections suggest that a seasonally ice-free Arctic — defined as less than 1 million km^2 of sea-ice extent in the summer — is likely to occur by 2050 (or even as soon as 2035) owing to positive feedback mechanisms that increase sea-ice loss[14–16]. This critical point will have important environmental, geopolitical, economic and societal consequences[17–19]. In the Antarctic, no statistically significant change has been reported in the mean annual extent of sea ice over 1979–2024, but its interannual variability has shown a marked increase, with extremes shifting from a record maximum extent in 2014 to a record minimum extent in 2023 (Fig. 1). In particular, record lows in summertime sea-ice extent have occurred in each of the past 4 years (2022–2025)[20–22].

Although satellite retrievals of sea-ice extent represent the longest continuous record of sea-ice observations, they provide a limited metric of polar climate change. Several unknown factors arise from the increasing variability in sea-ice coverage, such as temperature and cloud feedback processes[23,24], ocean heat exchange[25] and mid-latitude connections[26], which point to the need for an improved understanding of changing sea-ice properties and processes. Additional descriptors of the changing state of the sea-ice system, including sea-ice thickness, snow depth and surface albedo, have shown promise for use in climate monitoring and prediction, as they help to constrain feedback processes and disentangle natural climate variability from anthropogenic climate change. For instance, knowledge of sea-ice thickness is necessary to support process studies and seasonal forecasts, as this property integrates the thermodynamic and dynamic processes that control sea-ice growth and decay. As such, Arctic sea-ice thickness is expected to decrease more strongly than sea-ice extent in response to climate warming[27], which makes Arctic sea-ice thickness a valuable marker for measuring the effects of global climate on the Arctic climate system and vice-versa.

In this Review, we go beyond trends in sea-ice coverage to summarize how sea-ice properties and processes have changed in response to natural climate variability and anthropogenic climate change. We provide a broad summary of sea-ice change that complements the long-term record of sea-ice coverage. For the purposes of this Review, we compiled available Arctic and Antarctic sea-ice data and computed updated trends in sea-ice properties and dynamics (as detailed in the Supplementary Information). We produced the majority of results included in Figs. 1–6 and numbers reported in the text that are not accompanied by citations, which we put into context via a comprehensive summary of the literature on the topic. We bring together results of Arctic and Antarctic thermodynamic and dynamic properties and processes, including changes in sea-ice age, thickness, sea-ice season and melt season characteristics, snow depth, surface albedo, motion, surface roughness and polynya occurrence, and discuss the potential impacts of their changes on key atmosphere–ice–ocean feedback mechanisms. Finally, we present an outlook on critical knowledge gaps and joint model and observational priorities that could aid in the development of a more-holistic understanding of the Arctic and Antarctic sea-ice systems and their role in global climate.

Arctic and Antarctic sea-ice environments

Geography determines most of the differences between Arctic and Antarctic sea ice (Fig. 2), as well as the dominant drivers of their variability and response to climate change. The high Arctic Ocean is almost entirely confined by land (Fig. 1), which restricts sea-ice export and largely insulates the Arctic ice pack from the effects of storm-driven winds, waves and warmer waters of the north Atlantic and Pacific Oceans. Arctic sea-ice circulation is dominated by a persistent gyre in the Canadian Basin that is driven by the Beaufort High, a persistent high-pressure atmospheric system situated over the Beaufort Sea[28]. The atmospheric pressure ridge created by the Beaufort High and the lower atmospheric pressures over Eurasia create the Transpolar Drift Stream, a persistent flow that pushes sea ice towards Greenland and the Canadian Arctic Archipelago and drives the primary export of Arctic sea ice through Fram Strait. This land-mediated confinement enables sea ice to persist in the central Arctic for many years, in which it reaches a mean thickness of several metres[8,29]. Freshwater from Arctic rivers is similarly confined, which contributes to strong stratification that restricts deep ocean heat from reaching the underside of the sea ice[30], a thermodynamic mechanism that enables Arctic sea ice to grow much thicker than Antarctic sea ice (Fig. 2). By contrast, the Arctic peripheral seas are exposed to the warmer waters of the open ocean and frequent storms, and consequently, their winter sea-ice coverage is moderated by influences analogous to those in the Antarctic.

In the Antarctic, the seasonal expansion of sea ice is driven by southerlies in the gyres of major embayments in the Ross and Weddell Seas and the northward Ekman transport within the persistent westerlies of the Southern Ocean. At its northern boundary, the Antarctic sea-ice pack is not constrained by land (Fig. 1) but instead is shaped by exposure to frequent, strong storms, winds and waves, which govern the strong spatiotemporal variability in sea-ice coverage[31]. The Southern Ocean shows weak stratification due, in part, to the northward export of surface freshwater[32], which causes upward ocean heat flux from the warmer, deeper waters and thereby limits winter sea-ice growth[33]. Together, these forces create a dynamic Antarctic ice pack that contains more open water and leads (dynamic openings in the ice), has thinner ice and is covered by deeper snow than its Arctic counterpart (Fig. 2). The deep snow cover, divergent ice cover and exposure to warm upper ocean drive rapid summer melt of Antarctic sea ice, which occurs predominantly at the base of the sea ice and to a lesser extent on its surface. As a result, comparatively little Antarctic sea ice survives the melt season. However, Antarctic sea ice near the continental margins can grow many metres thick from being compressed against the shore. Buried under heavy snowfall and sheltered by the coast, this sea ice can persist through summer.

Differences in Arctic and Antarctic geography mediate the impacts of both internal and forced climate variability on sea-ice variability and change. Indeed, polar amplification of anthropogenic warming

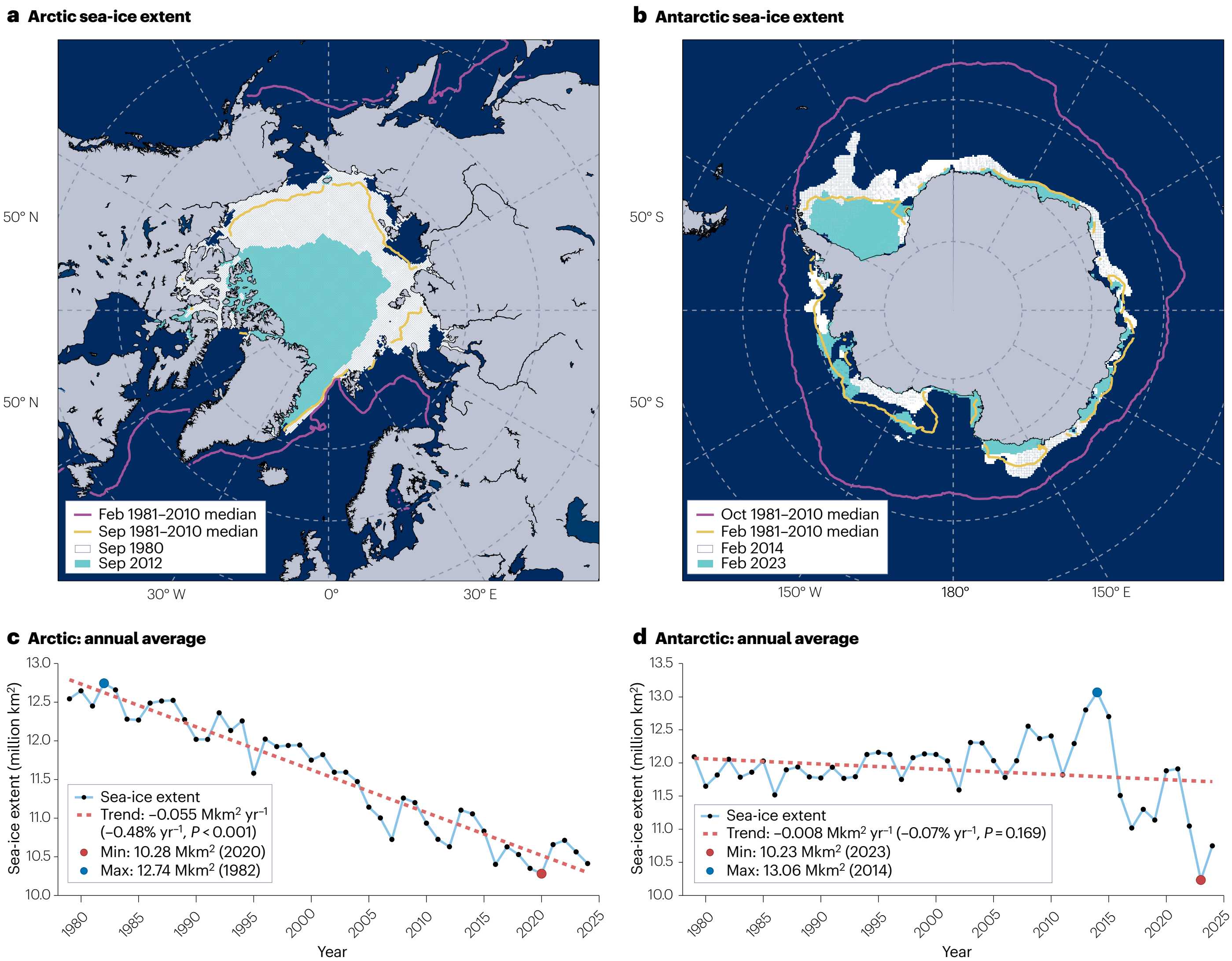

Fig. 1 | Change in sea-ice extent over 1979–2024. a–**d**, Maps of Arctic (**a**) and Antarctic (**b**) sea-ice extent. Contours show the 1981–2010 median sea-ice extent for February and October (magenta) and September and February (gold) corresponding to winter maximum and summer minimum sea-ice extents in the Arctic and Antarctic, respectively. Timeseries of annual average sea-ice extent are shown for the Arctic (**c**) and the Antarctic (**d**); the shaded white and light-blue areas indicate the monthly sea-ice extent in late summer (September in the Arctic and February in the Antarctic) during record high (**c**) and low (**d**) years. The dominant decreasing trend in the Arctic (0.55 million km^2 y^{-1}, $P < 0.001$) contrasts with the pattern of Antarctic sea-ice extent change. Sea-ice extents[245] were updated using computed bootstrap algorithm sea-ice concentrations.

is much stronger in the Arctic Ocean than in the Southern Ocean[34]. Both the influence of ocean heat uptake in the vast Southern Ocean[35,36] and differences in the strength of atmospheric feedback processes[37] contribute to these contrasting responses. Natural climate variability also has a larger influence in the Antarctic than in the Arctic, with strong teleconnections between tropical variability (particularly the El Niño–Southern Oscillation cycle) and storm tracks that ring the Antarctic[26]. These teleconnections can also be mediated through the ocean[38,39].

The hemispheric contrasts in observed trends and variability in sea-ice characteristics described in the following sections all emerge from these geographic differences. These differences relate to both the nature of the processes that govern Arctic and Antarctic sea-ice characteristics and to how geography modulates the atmospheric and oceanic forcing experienced by the Arctic and Antarctic sea-ice covers.

Thermodynamic and dynamic coupled properties

Age and thickness are two fundamental properties that characterize sea ice (Fig. 2). The thicker the sea ice is, the higher the likelihood that it can survive a summer melt season and grow older. Thus, sea-ice age and thickness are intricately linked and arise from the interplay between thermodynamic and dynamic processes. Here, we consider the importance of sea-ice age and thickness in the climate system, the decreasing trends in the Arctic and the notably large variability in the Antarctic. All trends reported in this Review have a statistical significance level of at least 95% (indicated by $P < 0.05$) unless otherwise noted (Table 1).

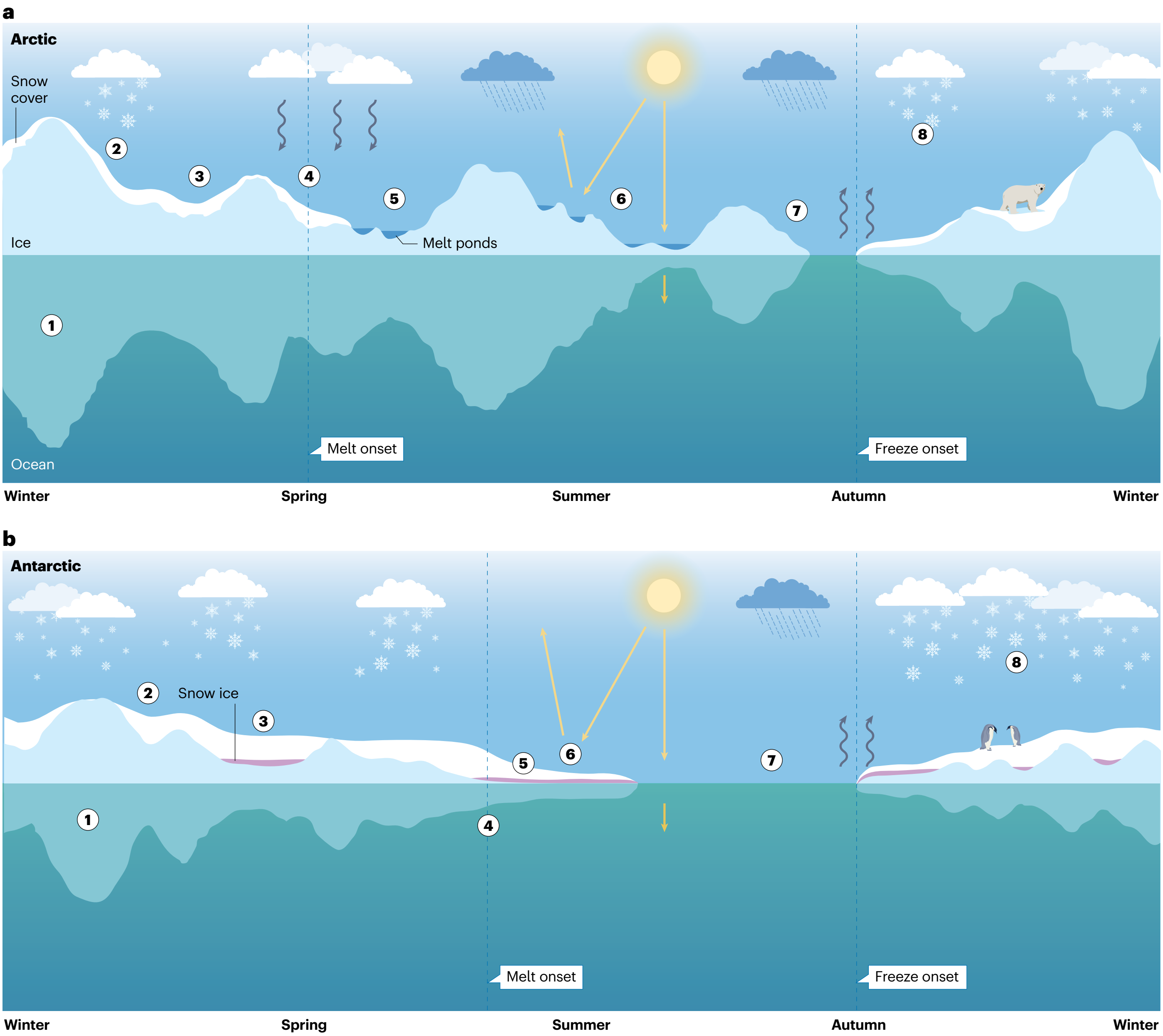

Fig. 2 | Sea-ice properties and processes in the Arctic and Antarctic environments, 1980–2010. a,**b**, Arctic (**a**) and Antarctic (**b**) sea-ice properties. (1) Sea-ice thickness substantially differs between hemispheres, with Arctic sea ice being thicker than that in the Antarctic. (2) Arctic sea ice tends to have greater surface roughness than Antarctic sea ice, owing to more perennial ice in the Arctic, which has had more time to undergo deformation and the rounding of ridges with summer melt. (3) The mean snow depth in spring in the Arctic is nearly half of that in the Antarctic. (4) In the Arctic, melt tends to start at the surface and is typically initiated by enhanced downwelling longwave radiation from stormy conditions or warm air masses. In the Antarctic, melt begins at the bottom of the sea ice from ocean heating. Antarctic surface melt is generally restricted to ephemeral, partial melt of the snow cover. (5) Most snow melts away in the Arctic, forming melt ponds on the surface. In the Antarctic, the snow cover persists and, if sufficiently deep relative to the ice thickness, causes flooding and snow-ice formation. (6) The surface albedo of Arctic sea ice is generally lower than that of Antarctic sea ice due to the presence of melt ponds, which allow more sunlight into the upper ocean, compared with the perennial snow cover of Antarctic sea ice. (7) Sea ice in the Arctic tends to persist throughout summer and become perennial ice, whereas the Antarctic has a seasonal ice regime, in which most sea ice melts away each summer. (8) The peak snowfall in the western and central Arctic tends to occur in autumn, whereas heavy, frequent snowfall occurs throughout the sea-ice growth season in the Antarctic.

Sea-ice age. The age of sea ice strongly influences how it interacts with the climate system. When sea ice persists from year to year, its thermal and electromagnetic properties evolve[40,41]. In the Arctic, meltwater flushing freshens perennial ice, which makes the ice mechanically stronger[42] and also provides a freshwater source for Arctic coastal communities[43]. The older that sea ice becomes, the rougher and thicker it tends to be owing to the cumulative effects of ice deformation and multiyear growth[29]. As a result, the spatial and temporal distributions of snow[44] and melt ponds[45,46] and the partitioning of incident shortwave radiation[2,3,47] strongly vary with sea-ice age. For these reasons, the age of sea ice is often used to define distinct sea-ice regimes in the Arctic and Antarctic. When a sea-ice floe survives its first summer melt season, it is considered perennial (old) ice, whereas if it survives two or more melt seasons, it is considered multiyear ice[48].

In the Arctic, an unprecedented shift towards a seasonal ice regime has occurred[10,49] (Fig. 3a). The area of sea ice that is at least 3 years old in March, the month with the largest ice area, decreased by 0.74% per decade over 1984–2024. This loss was accompanied by a corresponding increase (0.63% per decade) in first-year and younger ice. The year 2007 was an exceptional one for perennial ice loss, with a 46% decrease from the 1984–2006 mean[8,9,40]. From a regional perspective, the greatest losses occurred in the Beaufort, Chukchi and East Siberian

Table 1 | Summary of reported trends in sea-ice properties and processes

Domain	Source data (season)	Trend	Period	Refs.
Sea-ice extent				
Arctic	Passive microwave, sea-ice concentration satellite retrieval (annual)	−4.8% per decade	1979–2024	245
Antarctic	Passive microwave, sea-ice concentration satellite retrieval (annual)	n.s.	1979–2024	245
Age (multiyear ice coverage)				
Arctic	Passive microwave, ice-type satellite retrieval (spring)	−0.74% per decade	1984–2024	249
Antarctic	Passive microwave, minimum area from ice concentration satellite retrieval (summer)	n.s.	1979–2024	245
Thickness				
Arctic, submarine data release area	Submarine, satellite/airborne radar and laser altimetry, ice thickness retrieval (winter)	1.6 m total	1980–2023	68
Sea-ice season				
Arctic	Passive microwave, sea-ice concentration satellite retrieval	−11.6 days per decade	1979–2024	245
Antarctic	Passive microwave, sea-ice concentration satellite retrieva-	−1.6 days per decade	1979–2024	245
Melt onset				
Arctic (continuous melt onset)	Passive microwave, melt onset satellite retrieval	1.8 days per decade	1979–2024	11
Antarctic (temporary melt onset)	Passive microwave, melt onset satellite retrieval	n.s.	1979–2024	105
Freeze onset				
Arctic	Passive microwave, freeze onset satellite retrieval	5.6 days per decade	1979–2024	11
Melt season length				
Arctic	Passive microwave, melt onset and freeze onset satellite retrieval	7.4 days per decade	1979–2024	11
Snow depth				
Arctic	In situ, autonomous buoy, airborne/satellite retrievals (spring)	−2.5 cm per decade	1954–2024	See data availability
Antarctic (Weddell Sea)	Autonomous buoy (spring)	n.s.	2013–2024	136,137
Albedo				
Arctic	Passive reflectance imaging, satellite retrieval (summer)	−0.030 per decade	1979–2020	243
Antarctic	Passive reflectance imaging, satellite retrieval (summer)	0.002 per decade	1979–2020	243
Motion (drift)				
Arctic	Passive microwave, satellite retrieval (spring)	0.63 cm s^{-1} per decade	1978–2024	250
Antarctic	Passive microwave, satellite retrieval (spring)	0.69 cm s^{-1} per decade	1982–2024	250
Polynya occurrence				
Arctic (north of 59° N)	Passive microwave, sea-ice concentration satellite retrieval (winter)	2.4 days per decade	1979–2023	251
Arctic (south of 59° N)	Passive microwave, sea-ice concentration satellite retrieval (winter)	−1.6 days per decade	1979–2023	251
Antarctic (Pacific sector)	Passive microwave, sea-ice concentration satellite retrieval (annual)	3.2 days per decade	1979–2023	251
Antarctic (Amundsen and Bellingshausen sectors)	Passive microwave, sea-ice concentration satellite retrieval (annual)	−2.2 days per decade	1979–2023	251

No data are available for Antarctic sea-ice thickness, freeze onset or melt season length. n.s., no statistically significant trend.

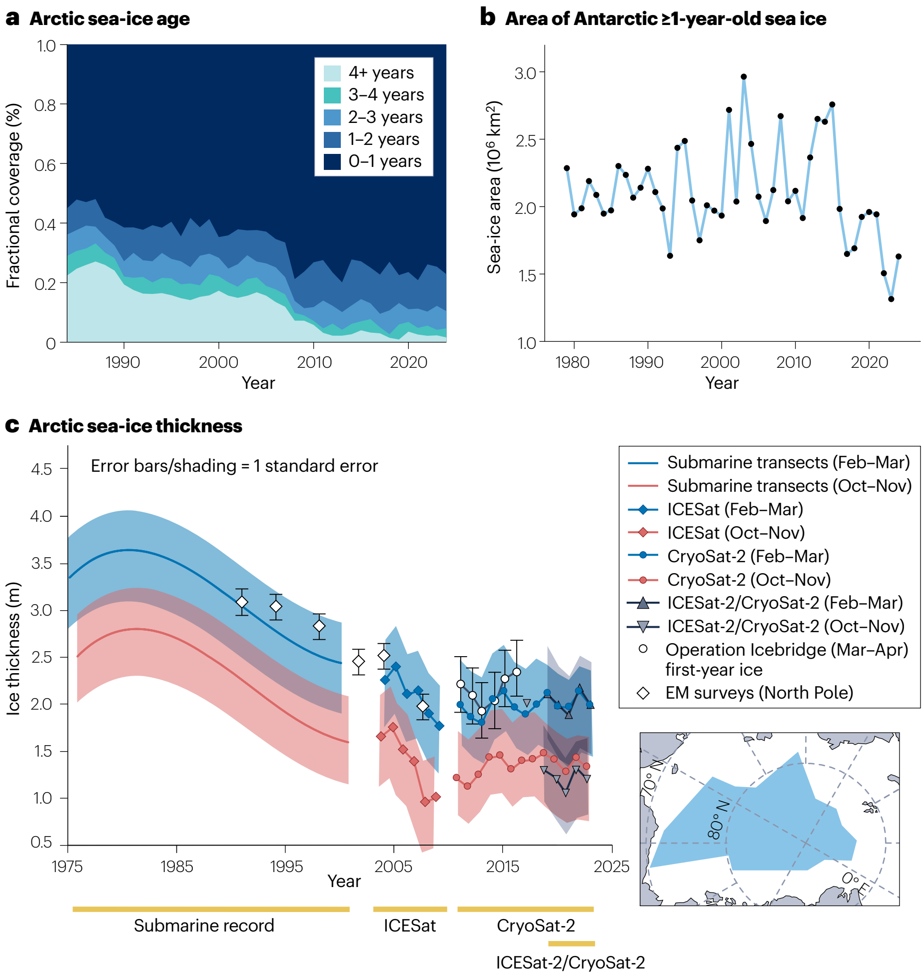

Fig. 3 | Arctic and Antarctic estimates of sea-ice age and mean Arctic sea-ice thickness. a, The fractional coverage of Arctic sea ice of different ages[249] during 1984–2024. **b**, The area of remaining sea ice[245] at the end of the Antarctic melt season[245], which is representative of Antarctic sea ice that is at least 1 year old, for 1979–2024. **c**, The Arctic compilation of submarine, surface-based (derived from electro-magnetic induction, EM), airborne and satellite sea-ice thickness retrievals for 1975–2023. Uncertainty in Antarctic thickness changes from satellite estimates remains greater than any observed circumpolar trends. Arctic sea-ice age and thickness have declined since the 1980s and 1970s, respectively. Part **c** adapted from ref. 68, CC BY 4.0.

sectors, whereas the remaining perennial ice persists in the central Arctic[10]. Perennial ice is now younger, with 2–3-year-old ice making up >50% of the perennial ice cover in 2013–2023, compared with 25% in 1990–2000. This loss of perennial ice has contributed to atmospheric warming[50–52] and disruptions to the regular functioning of the Arctic marine ecosystem. Compared with multiyear ice, seasonal ice is less favourable for sympagic phytoplankton species and grazers[53,54] and less stable for marine mammal haul-outs[6]. The ongoing loss of perennial ice is having profound effects on Arctic coastal communities as well as the Arctic ecosystem and climate system.

The Antarctic contains considerably less perennial ice than the Arctic, and the perennial ice that does exist tends to be comparatively younger than its Arctic counterpart. A perennial snow cover and the lack of sustained surface melt hinder reliable retrievals of Antarctic ice age with remote sensing methods; as a result, unlike in the Arctic, no comparable record of sea-ice age exists in the Antarctic[55]. Although the western Weddell Sea consistently has perennial ice, other Antarctic regions have had irregular periods of perennial ice over 1979–2024. In the Amundsen and Bellingshausen Seas, perennial ice has been intermittent since the early 1990s but has been less present over the 2010s[56–58]. Active and passive microwave satellite retrievals suggest that no statistically significant trends in perennial ice occurred in April–November over 2013–2023, although this timeseries was marked by large interannual variability[55]. The 1979–2024 timeseries of the annual minimum sea-ice area, a proxy for perennial ice area, also exemplifies this large interannual variability (Fig. 3b). Similar large variability has been observed for landfast perennial ice, the persistence of which depends on bathymetry, grounded tabular icebergs and other local, geographic features that protect the sea ice from wind and ocean forcing[59].

Sea-ice thickness. Over annual-to-multiyear time-scales, the distribution of sea-ice thickness integrates the thermodynamic and dynamic responses of the sea-ice cover to atmospheric and oceanic forcings[60]. Although mass changes at the interface between the atmosphere and ocean are governed by thermodynamic processes, sea-ice motion is responsible for the mechanical redistribution of the sea-ice cover through the formation of leads and pressure ridges (piles of highly deformed ice blocks). The thicker the sea ice becomes, the more resilient it is to summer melt, as more energy is then needed to completely melt the ice. Therefore, knowledge of the ice thickness distribution and its variability are crucial for understanding sea-ice processes and informing model predictions. Before the turn of the twenty-first century, sea-ice thickness monitoring in the Arctic was achieved by compiling ice draft measurements from submarine-based, upward-looking sonar[61,62]. Satellite altimetry has since transformed the monitoring of sea-ice thickness by providing sea-ice thickness estimates at unprecedented spatial and temporal scales[63–65]. In particular, novel techniques based on the synergy of dual-band altimeter observations are opening new avenues for the improved estimation of snow depth and sea-ice thickness[66,67].

Within the submarine data release area (which covers ~38% of the Arctic Ocean), an average sea-ice thinning of ~1.8 m occurred over 1958–2000[68]. Since 2000, three dedicated polar-orbiting altimetry missions have provided two decades of basin-wide coverage of Arctic sea-ice thickness. The combined timeseries of submarine and satellite datasets (1975–2023) reveals that winter ice thickness now hovers around 2.0 m with fall ice thickness at 1.3 m, down from a 1980 winter peak of 3.6 m and fall peak of 2.7 m (ref. 68) (Fig. 3c). The Arctic-wide thinning of sea ice, which was primarily driven by the decline in perennial ice between 2003 and 2007, has since slowed as seasonal ice has become more prevalent (Fig. 3a). This slowdown in sea-ice thinning corresponds with the hiatus in the decline in sea-ice extent[69].

In the Antarctic, no comparable in situ timeseries exists and large-scale observations are sparse. So far, the most extensive compilation of Antarctic sea-ice thickness remains the Antarctic Sea Ice Processes and Climate (ASPeCt) database[70], which initially contained observations from 83 voyages and 2 helicopter flights made during 1980–2005 and has since been updated (to 2019)[71]. Additional airborne surveys have provided valuable information on the interannual variability of sea-ice thickness in the Weddell Sea[72]. Yet, these datasets offer a limited spatial and temporal view of changes in Antarctic sea-ice thickness. Satellite altimetry has made some progress in mapping Antarctic sea-ice thickness[73–76], but (at the time of writing) different retrievals exhibit inconsistent long-term trends. For example, satellite-derived estimates of Antarctic sea-ice thickness reveal trends with opposing signs in the Weddell Sea but are broadly consistent in the coastal regions of the Amundsen and Bellingshausen Seas[74–76]. Satellite retrievals of Antarctic sea-ice thickness contain potentially large uncertainties[77] owing to the complex nature of the snow cover[78] and, therefore, remain an active area of research. Although these satellite-based assessments differ in periods, their differences underscore that the uncertainty in Antarctic sea-ice thickness retrievals is likely to be larger than the magnitude of estimated trends[79]. Such uncertainty remains difficult to quantify, as it depends on the retrieval algorithm used, the assumptions made and the data products used for snow properties (and their associated biases).

Thermodynamic properties and processes

Sea-ice thermodynamics describe the cyclical growth and melt of sea ice (Fig. 2), which are influenced by many factors. Air and ocean temperatures primarily dictate the timing and rate of sea-ice growth and decay and, as a result, largely determine the duration of the sea-ice season. Secondary factors include the state of the sea-ice surface (namely, bare, snow-covered, melt-ponded and/or optically thin), which affects both surface albedo and solar absorption in the ice–ocean system. Here, we consider the nature of the Arctic and Antarctic sea-ice seasons and melt seasons, their snow covers and surface albedo. These characteristics are described within the context of known climatological factors and observed changes.

Sea-ice season. The duration of the sea-ice season provides a spatial perspective on the interplay between sea-ice growth and melt processes and, to a lesser extent, sea-ice dynamics. The sea-ice season is defined as the total number of days that sea ice is present in a given area in 1 year. A shortening or lengthening of the sea-ice season has repercussions for the energy exchange between the atmosphere and ocean. For example, a shorter sea-ice season facilitates atmospheric warming via increased air–sea heat exchange in autumn and winter[80] and ocean warming via increased solar absorption in spring and summer[81]. Therefore, monitoring the sea-ice season provides contextual information for understanding how Arctic and Antarctic sea ice are changing and either counteract or amplify feedbacks within the climate system.

An updated analysis of existing data[82] shows that the Arctic sea-ice season dramatically decreased over 1979–2024 (Fig. 4a). In areas where the 1979–2024 average season was ≥10 days, the season has shortened by 11.6 days per decade. The peripheral seas exhibited the largest decrease, with statistically significant trends exceeding −60 days per decade in the northern Barents Sea and far northern Kara Sea, which is consistent with previously reported trends[82]. Although Arctic sea-ice coverage decreased in all months, the greatest losses occurred in late summer and early autumn[83]. The reduction in the Arctic sea-ice season is strongly related to the long-term changes in its melt season characteristics, snow depth and surface albedo, aspects of which are discussed below.

By contrast, changes in the Antarctic sea-ice season are regionally distinct and more complex than those in the Arctic (Fig. 4b). Our updated analysis of previously published data[84] shows a prominent reduction in the sea-ice season in the Amundsen and Ross Seas over 1979–2024. Decreasing trends in sea-ice season duration have also developed to the north of the Weddell Sea and span parts of the Indian Ocean, Amundsen Sea and Bellingshausen Sea. The increasing trends in the sea-ice season previously observed in the northern and western Ross Sea[84] are now present in only a small region of the western Ross Sea. The anomalous increasing trends in the sea-ice season in the eastern Weddell Sea are new (that is, they developed after 1979–1999)[84]. The trend for the entire Antarctic domain is a decline of 1.6 days per decade for 1979–2024 that, relative to the Arctic trend, is more-weakly related to surface melt, snow depth and surface albedo changes. Rather, sea-ice advection and exposure to warm ocean waters are the main factors that influence the duration of the Antarctic sea-ice season[85].

Melt season characteristics. The onset of melt marks an inflection point in the seasonal cycle, after which the mean sea-ice area and thickness begin to decrease. The Arctic and Antarctic melt seasons show distinct differences in their duration, intensity and ice melt[85,86]. In the Arctic, melt onset typically begins at the snow surface and is often initiated by enhanced downwelling longwave radiation from synoptic weather systems and the advection of warm, cloudy air masses[87–89]. Arctic melt typically begins with freeze–thaw cycling within the snow cover, which is known as early melt onset. Following early melt onset, a period of sustained surface melt begins, known as continuous melt[11]. The initiation of early melt onset and continuous melt onset precede the dramatic albedo reduction[3] associated with more-advanced stages of surface melt, such as melt ponding[90]. Under the ice, bottom melt starts at a similar time to surface melt, albeit with regional and interannual differences[91,92]. By contrast, Antarctic melt onset tends to start at the bottom of the ice and is often driven by the advection of ice into warmer, more northerly waters and by solar heat input in open water within the divergent ice pack[86,93,94]. Surface melt in the Antarctic is attenuated relative to its Arctic counterpart[93,95]. In essence, Antarctic sea ice tends to melt primarily from the bottom up and internally[96], whereas Arctic sea ice primarily melts from both the bottom up and top down[91].

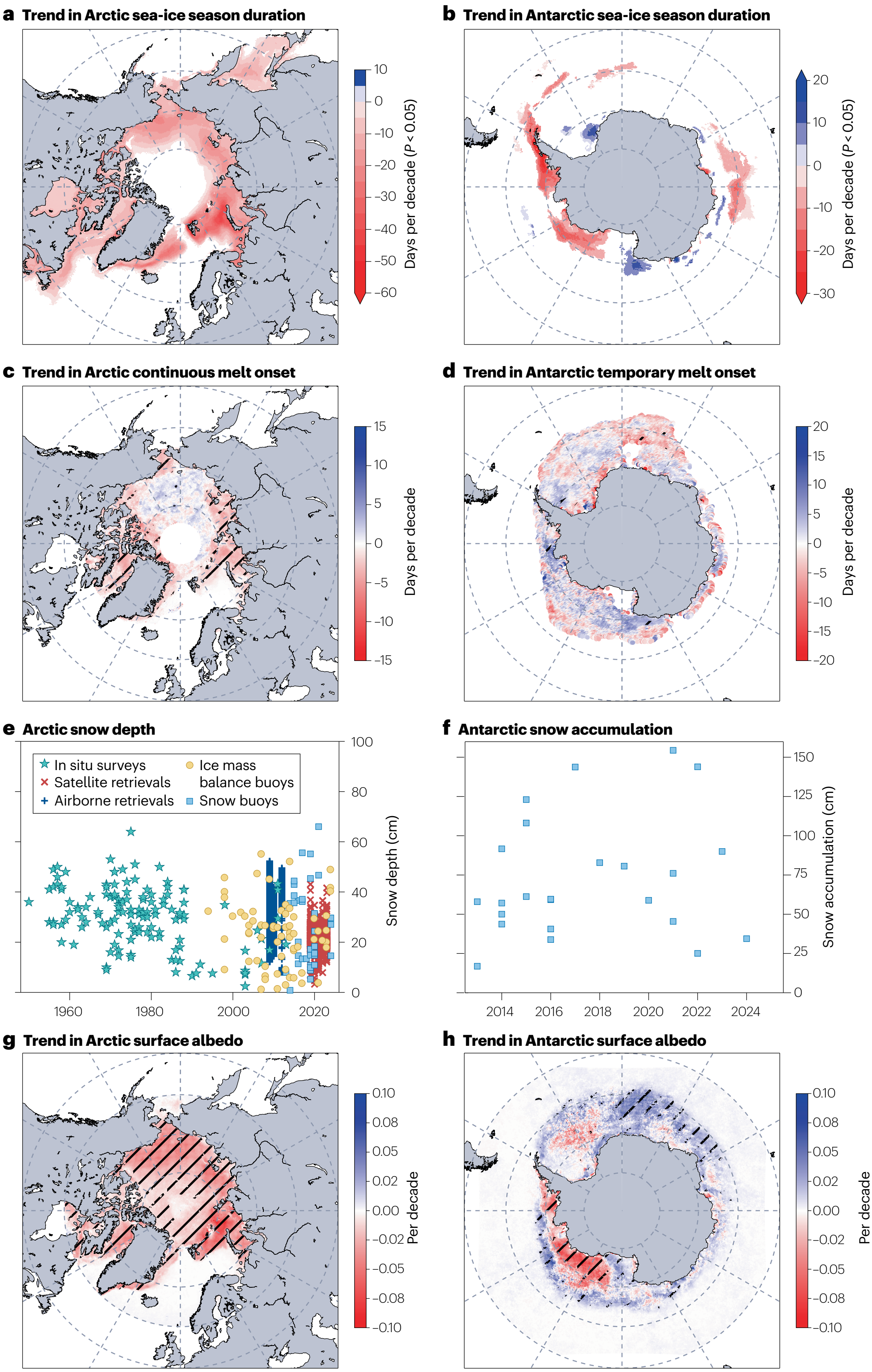

Fig. 4 | Trends in sea-ice thermodynamic characteristics for 1979–2024. a–h, Arctic (**a**) and Antarctic (**b**) sea-ice season durations[245] over 1979–2024. Trends in the Arctic date of continuous melt onset[11], defined as the day after which sustained surface melting conditions occur (**c**). Trends in the Antarctic date of temporary melt onset[105], defined as the first occurrence of temporary surface snowmelt (**d**). The snow depth timeseries for the Arctic over 1954–2024 using a combination of airborne and satellite retrievals, in situ surveys and autonomous drifting buoys (**e**), and the snow accumulation timeseries for the Weddell Sea over 2013–2024 from autonomous drifting buoys (**f**). Arctic trends in clear-sky surface albedo[243] in summer relative to 1979–1998 (**g**). Antarctic trends in clear-sky surface albedo[243] in summer relative to 1979–1998 (**h**). In map parts **c**, **d**, **g** and **h**, hatching indicates regions with significant trends ($P < 0.001$).

In the Arctic, high-frequency changes in passive microwave brightness temperatures (that is, the natural microwave radiation emitted by the Earth's surface) are used to identify dates of surface melt onset, freeze onset and melt season duration[11,97,98]. The Arctic melt season begins in late spring in the seasonal ice zone and progresses northwards to the central Arctic by early summer[12,13]. However, statistically significant shifts in the Arctic melt season occurred during 1979–2024[11]. In latitudes above 65° N, surface melt onset now occurs earlier (by ~1.8 days per decade) and freeze-up occurs later (by ~5.6 days per decade), which has resulted in an overall lengthening of the Arctic melt season by ~7.4 days per decade (Fig. 4c). The trend towards later freeze onset is evident in all regions excluding the central Arctic[99], which is consistent with the observed patterns of Arctic sea-ice loss[100] (Fig. 1). In regions where earlier sea-ice retreat coincides with periods of high net solar radiation, sea surface temperatures have increased through a positive ice–albedo feedback[101,102], which further delays the freeze-up of sea ice[100,103].

Compared with that in the Arctic, the melt season in the Antarctic is considerably shorter (by ~1 month) and more rapid[86]. Nonetheless, the seasonal retreat of Antarctic sea ice is larger, occurring over 5 million square kilometres[58,83]. The majority (~39%) of Antarctic surface melt occurs as diurnal freeze–thaw cycling, whereas <2% of melt events are continuous melt[104,105]. Accordingly, the passive microwave satellite record shows no substantial trends in ephemeral or continuous surface melt onset dates in the Antarctic[105,106] (Fig. 4d). The large variability in Antarctic surface melt onset dates[105–107], together with the record lows in Antarctic sea-ice extent in the past 4 years (2022–2025)[20–22], suggest that surface melt onset has little or no relationship with Antarctic sea-ice coverage. Rather, ocean heat is an important source of Antarctic sea-ice melt and has contributed to the recent record declines in Antarctic sea-ice coverage in the same time period[20,85,108]. Openings within the divergent Antarctic ice pack might also enable sufficient solar absorption to cause a positive ice–albedo feedback, leading to rapid bottom and internal ice melt[93,94,109].

Snow depth. Snow is one of the most reflective[110] and insulating[111,112] natural materials on Earth. These unique properties — and the large expanse of snow-covered regions — make snow a key component of climate and sea-ice systems[113]. During the sunlit seasons, snow shields the sea-ice surface from solar radiation[2,3], which reduces sea-ice melt and solar heating of the ice–ocean system[102]. Snow on sea ice is also an essential component of polar marine ecosystems because it creates low-light conditions suitable for sympagic algae[53,114] and vital denning habitat for marine mammals[115,116]. Although sea-ice growth is inhibited by the presence of snow[117,118], if sufficiently deep, the weight of the snow cover can depress the sea-ice surface below sea level, which causes flooding at the base of the snowpack. Upon freezing, the resulting snow-ice provides a positive mass contribution to sea ice[119]. Thus, snow and sea-ice conditions are intricately linked in numerous ways[44,120].

In the central Arctic, the best evidence suggests that the spring snow cover has thinned by 2.5 cm per decade over 1954–2024, from a mean depth of 36 cm in the 1950s (Fig. 4e). The greatest thinning has occurred in the Beaufort and Chukchi Seas[121]. There, the loss of perennial ice[8,40] and later freeze-up[11] have reduced snow accumulation during September–November, the peak in the snowfall cycle[121]. By contrast, snow depth in the Lincoln Sea and Fram Strait has shown no substantial change over the same period. This difference might, in part, be due to the proximity of the North Atlantic storm track to the Lincoln Sea and Fram Strait regions[122–124], which brings frequent, heavy snowfall and results in large year-to-year variability in snow depth[125,126].

Although the 1954–2013 snow accumulation timeseries suggests that snowfall in the central Arctic has not changed substantially[121], multiple reanalysis (modelled) precipitation timeseries show that an increasing proportion of precipitation is now coming in the form of rain[127]. As a consequence, more rain-on-snow events have occurred earlier in spring (trend 4–6 days per decade over 1980–2017); these events might contribute to a 0.5 cm per decade thinning of the spring snow cover[128], which has important implications for surface albedo and subsequent melt rates. In the Arctic, most snow melts away each summer[129–131], which leads to the formation of melt ponds and a reduction in the surface albedo[45,132]. Hence, the maximum snow depth attained before late spring governs the duration of a highly reflective surface during peak insolation[126].

Unlike in the Arctic, snow on Antarctic sea ice tends to persist throughout the sea-ice melt season and forms a high-albedo, perennial snowpack[119]. The greater snow load on the thinner sea ice facilitates widespread flooding and snow-ice formation, as well as salt wicking up into the snow[119,133,134]. Freeze–thaw cycling leads to ice layers throughout the snowpack and superimposed ice formation at the base. Together, these phenomena create a more-complex vertical substrate of snow on Antarctic sea ice relative to snow on Arctic sea ice. The complex snow conditions on Antarctic sea ice poses considerable challenges for accurate remote sensing retrievals of snow depth[135]. Thus, the timeseries of Antarctic snow depth is substantially more limited than its Arctic counterpart owing to limited remote sensing retrievals, as well as the scarcity of in situ observations. Flooding and snow-ice formation complicate autonomous measurements by buoys[136], which as a result measure the cumulative snow accumulation rather than snow depth[137]. In the Weddell Sea, one of the most-sampled regions by buoys, no statistically significant trend in snow accumulation has been observed over 2013–2024 (Fig. 4f).

Advances in altimetry[73] and passive microwave[138] remote sensing are starting to reveal a more complete picture of the spatiotemporal patterns in Antarctic snow. In the Ross Sea, where some of the thinnest snow conditions occur[73], passive microwave retrievals suggest that snow depth has thinned in all seasons (over 2002–2020)[138]. Other spaceborne observations have shown no trends, which is probably due to their relatively short timeseries. Although these early glimpses from spaceborne measurements are promising for the future monitoring of snow, they could be subject to large uncertainties given the complexities of Antarctic snow conditions, which highlights the need for surface-based snow monitoring and validation efforts.

Albedo. The ice–albedo feedback is one of the most consequential phenomena in Earth's changing climate. With diminishing sea-ice coverage, the highly reflective sea-ice cover is replaced by the dark ocean surface, which increases the absorption of solar radiation and, in turn, leads to further sea-ice melt. Therefore, sea-ice loss causes the climate system to gain energy through a positive feedback, and the planet warms[139–142]. Both the presence of sea ice[141,143] and the state of its surface (namely, snow-covered, ponded and/or bare) govern the surface albedo in the polar seas[3,144,145]. Thus, trends in albedo can be considered from two perspectives: the changes associated with the loss or gain of sea ice itself, and the changing state of the sea-ice surface, such as thinning snow or increasing melt pond coverage, over time.

The ice–albedo feedback is also modulated by the presence and optical properties of clouds, which have a substantial effect: at least half of the variability in sea-ice albedo is 'masked' by cloud cover[142,146,147]. However, in terms of decadal trends in the polar ice–albedo feedback, cloud-masking effects seem to vary much less than the surface albedo changes that result from variations in sea-ice coverage and surface properties. For this reason, although we emphasize that clouds are critically important in shaping the overall energy budget of sea-ice regions, in this Review, we focus on sea-ice surface albedo and its variability.

In the Arctic, clear-sky albedo has decreased by 0.03 per decade over 1979–2020 (Fig. 4g). This decrease is predominantly driven by the reduction in Arctic sea-ice coverage. As such, the 2007–2024 hiatus in Arctic sea-ice decline[69] could result in a smaller decreasing trend in surface albedo over the same time period. Nonetheless, for 1979–2020, the largest decrease in albedo (−0.05 per decade) occurred in the Barents and Kara Seas and spatially coincides with the largest increase in annual mean temperature in the Arctic, exceeding 1.25 °C per decade (1979–2021)[148]. The Beaufort and Chukchi Seas have also exhibited a large decrease in albedo (−0.04 per decade over 1979–2020) resulting from the loss of perennial ice, the increasing extent of open ocean, and the subsequent increases in solar absorption and ocean heat[101,102].

The central Arctic and Lincoln Sea have exhibited the smallest decrease in albedo (−0.02 per decade) over 1979–2020 owing to persistent sea-ice coverage. In areas with at least 80% sea-ice concentration, the detrended June–July albedo and fraction of ponded sea ice are strongly inversely correlated ($r = -0.77$). Although melt pond coverage drives year-to-year anomalies in midsummer albedo, these anomalies in midsummer albedo are collectively determined by the areal coverage and optical properties of snow, bare ice and ponded ice. As shown in model simulations[149], early melt pond formation leads to a diminished extent of late-summer sea ice through a positive albedo feedback. Although natural climate variability has an important (albeit diminishing) role in governing the interannual changes in summer snow depth[126], emerging critical questions revolve around the future magnitude and phase of precipitation over the sea ice and its impact on surface albedo. Coupled Model Intercomparison Project Phase 6 (CMIP6) model projections point towards a wetter and increasingly rain-dominated Arctic by the end of the twenty-first century, which has adverse implications for the surface reflectivity of the remaining sea-ice cover[150].

Compared with trends in the Arctic, pan-Antarctic trends in clear-sky albedo are considerably more muted, increasing by 0.002 per decade over 1979–2020 (Fig. 4h). This small trend is a result of the disparate albedo trends between Antarctic regions and the sea-ice surface state remaining relatively invariant owing to a persistent snow cover. For example, in the Bellingshausen and Amundsen Seas, albedo has decreased by 0.04 per decade. In those regions, the decreasing October–May sea-ice coverage has exposed more open ocean, thereby decreasing the surface albedo during the sunlit months. By contrast, eastern Antarctic sectors have exhibited an increase in albedo (0.03 per decade over 1979–2020), although this trend only reached statistical significance in northerly areas of the ice pack, in longitudes 0–60° E. Because snow tends to persist throughout the Antarctic melt season[119] and melt onset dates have not changed[105,106], trends in Antarctic albedo are presumed to be caused by changes in the spatiotemporal patterns of the sea-ice cover rather than its surface state.

Dynamic processes and properties

Sea ice is a dynamic medium, and its dynamics modulate the energy exchange between the atmosphere and the ocean. Sea ice moves in response to the winds and ocean currents, drifting in large-scale patterns that are shaped by low and high air pressure systems, ocean gyres and land masses. These motions bring about mechanical redistribution of the sea-ice cover to form ridges, rafted ice and shear zones (Fig. 2). Unlike thermodynamic processes, which shape the sea-ice cover over relatively long time-scales, dynamic processes can occur rapidly, on the order of hours[151]. These dynamic features create variable undulations in the sea-ice surface that have cascading thermodynamic and dynamic effects on the atmosphere, sea ice and ocean. In some situations, the presence of strong winds or warm, upwelling water creates large, persistent openings within the ice pack, termed polynyas, which serve as biological hotpots and sea-ice factories in the polar and sub-polar seas. Here, we present the observed changes in sea-ice motion (also termed drift), surface roughness and polynya occurrence.

Sea-ice motion. Sea-ice motion affects the momentum exchange between the atmosphere and ocean[152,153], the transport of sediment[154] and pollutants[155–157], and the residence time of sea ice in polar regions[158]. Sea ice typically moves 4–5° from the geostrophic winds owing to the Coriolis effect[159,160], with variations that depend on the sea-ice thickness, internal stress and consolidation of the pack ice[161], atmospheric and ocean drag[162,163], speed and direction of the underlying ocean flow[152,153], and proximity to land[159]. Near the coast, sea-ice motion usually has a weaker response to geostrophic winds[159], and shear zones often exist between the landfast ice and drifting pack ice. As sea ice seasonally evolves, the speed and direction of sea ice also change. For example, floes in marginal ice zones often undergo free drift in summer[153]. Sea-ice motion is also affected by atmospheric variability (for example, the Arctic Oscillation[160] and the Southern Annular Mode[164]) because surface winds are the dominant force behind sea-ice drift.

Much work has been done to characterize the seasonal and climatological patterns, variability[160] and trends in Arctic sea-ice motion[161,165–167]. Although the data and methods differ across studies, the reported trends all show the same pattern: that the drift of Arctic sea ice has increased[161,165–167]. Buoy data show that Arctic ice drift has increased by 0.74 cm s^{-1} per decade in winter and 0.59 cm s^{-1} per decade in summer over 1979–2009[166]. The increase in drift has been attributed to kinematic processes that promote sea-ice thinning and to a mechanically weaker ice pack with openings that contribute to a positive ice–albedo feedback[166]. Other studies have attributed the increased drift solely to thinner sea ice[161,166] or to a combination of that and stronger wind forcing[167], with regional variations in their influence.

The passive microwave satellite record for 1978–2024 shows that Arctic ice drift in February–March has increased by 0.63 cm s^{-1} per decade (Fig. 5a). The spatial pattern of trends suggests that the thinning Arctic sea-ice cover is becoming increasingly responsive to the Beaufort Gyre circulation and Transpolar Drift Stream, which might lead to increased openings in the ice pack. More openings increase heat flux to the atmosphere in winter and solar absorption in the ocean in spring, both of which contribute to Arctic warming. Increased drift speeds also have implications for the rate of sea-ice export out of the Arctic, as the largest trends occur in Fram Strait (1.34 cm s^{-1} per decade) and Baffin Bay–Nares Strait (0.95 cm s^{-1} per decade), two major ice export gateways[168,169].

The understanding of patterns, trends and variability in Antarctic sea-ice motion is more limited than for the Arctic owing to the relative paucity of observations. Furthermore, the dynamic nature of an unbound sea-ice edge creates large uncertainties in satellite retrievals of Antarctic sea-ice motion. Thus, most Antarctic timeseries begin in

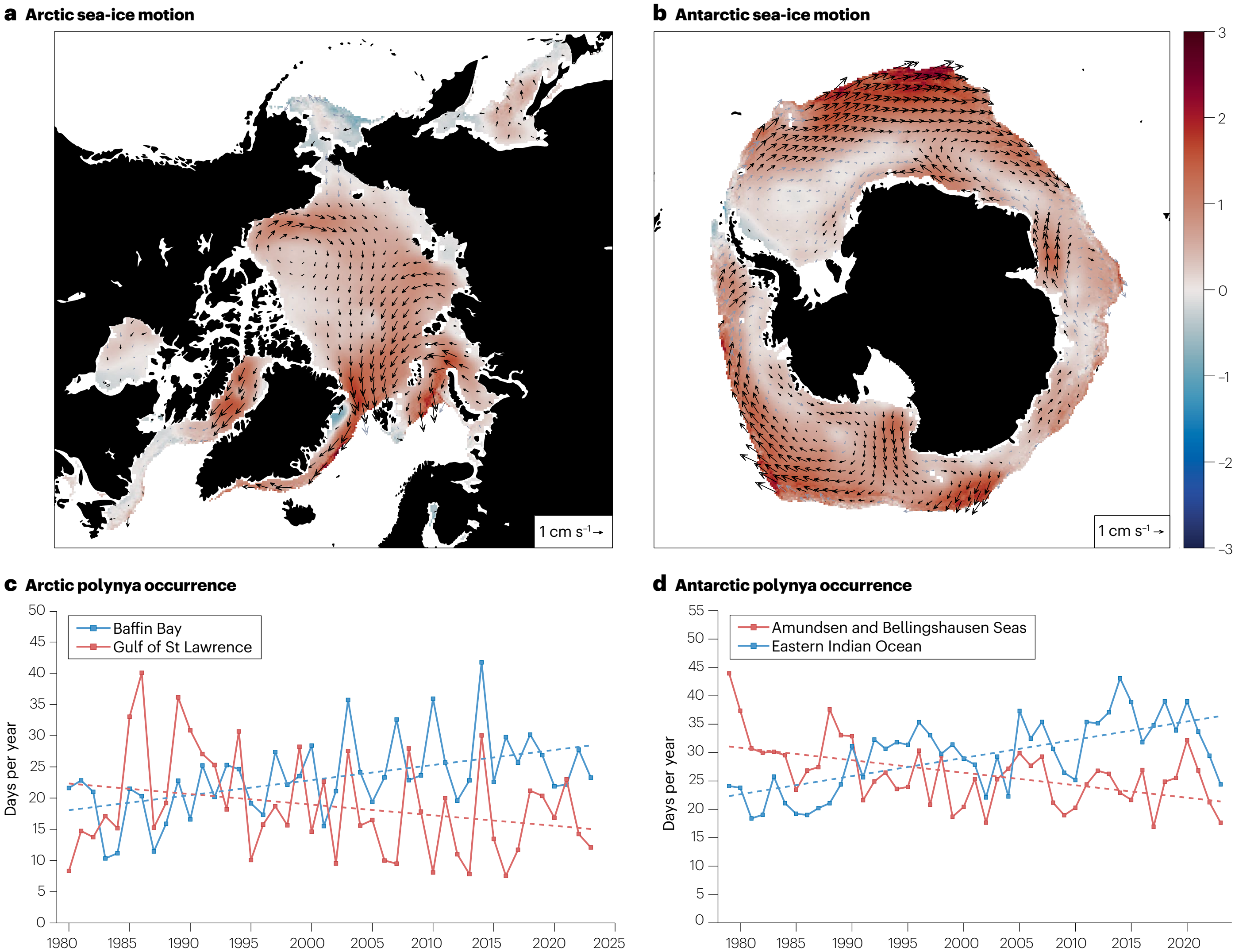

Fig. 5 | Changes in sea-ice motion and polynya occurrence in the Arctic and Antarctic. a–d, Trends in sea-ice motion[250] over the Arctic (1978–2024) (**a**) and the Antarctic (1982–2024) (**b**). Vector arrows in black indicate areas with at least 95% statistical significance ($P < 0.05$), whereas light-grey vector arrows are not statistically significant. Trends in polynya occurrence[251] over 1979–2023 for two contrasting regions in the Arctic (**c**) and Antarctic (**d**).

1982 or later, when passive microwave retrievals became more frequent. These timeseries show that large-scale sea-ice motion largely influences the extent of the Antarctic ice pack and that the sea-ice motion itself is strongly affected by atmospheric variability[164,170,171]. In fact, geostrophic winds alone explain ~60% of the variance in wintertime drift[170]. Antarctic sea-ice motion during the 1992–2010[172] and 1982–2015[170] periods exhibited spatial variability that has been attributed to trends in the large-scale wind fields[170,172].

Over 1982–2024, the pan-Antarctic ice drift for September–October has substantially increased by 0.69 cm s^{-1} per decade (Fig. 5b). The largest increases occurred along the Antarctic sea-ice edge (0.79 cm s^{-1} per decade), where the eastward ice drift is driven by westerly winds and the Antarctic Circumpolar Current[171]. In the Indian Ocean, sea-ice drift near the coast has increased by 0.87 cm s^{-1} per decade, which was driven by a 0.64 cm s^{-1} per decade increase in its zonal, westward drift. By contrast, ice motion in the Ross Sea is dominated by northerly ice advection, which is associated with an increase in sea-ice drift of 0.52 cm s^{-1} per decade (1982–2024). These results underscore the strong regional differences in atmospheric forcing and sea-ice response, which points to a need for improved understanding of atmosphere–ice interactions and their role in regional Antarctic sea-ice variability.

Surface roughness. Surface roughness describes the variation in the sea-ice surface, which undulates with ridges, rubble, hummocks, snow drifts, melt ponds and pans of undeformed ice. This variation governs the transfer of kinematic energy from the atmosphere to the ocean, which, in the broader context of ocean circulation, strongly influences upper ocean stratification and mixing in polar seas[152,153,162,163]. From a thermodynamic perspective, surface roughness affects the surface energy balance of the sea-ice system by influencing wind-driven snow redistribution[173] and (in the Arctic) melt pond coverage[45,46,174], which, in turn, modify the surface albedo and sea-ice melt rates. Hence, surface roughness plays an important part in the polar climate system by modulating dynamic and thermodynamic processes throughout the year.

The prevalence of seasonal ice (which is often smoother than perennial sea ice[175–177]) has increased in the Arctic since the 1980s[8,10]. With the shift to a seasonal sea-ice regime, the surface roughness characteristics of Arctic sea ice could also change. Seasonal ice is mechanically weaker than perennial ice and therefore deforms more easily. Deformation generates surface roughness, but the resulting morphological features of seasonal ice are typically smaller than those formed in multiyear ice. In the Lincoln Sea, a region characterized by perennial ice, a stark decrease occurred over 2004–2023 in both the mean ridge density (2.33 n km^{-1} per decade) and ridge height (0.14 m per decade)[177]. In 2007, upward-looking sonar in Fram Strait also captured a marked (52%) reduction in >4-m-thick, deformed ice relative to the 1991–2019 period[49]. A more muted decreasing trend in surface roughness has been observed over seasonal ice. Airborne retrievals of ridge density, height, and spacing over seasonal ice show little change during 1993–2023 in the Transpolar Drift region[177]. These results underscore the increased homogeneity of seasonal ice relative to that of perennial ice. Moreover, seasonal ice deformation largely depends on synoptic events, which are sporadic in nature and contribute to large interannual variability[178,179].

In the Antarctic, limited data are available on the surface roughness characteristics of sea ice. Consequently, whether decadal changes in roughness characteristics have occurred remains unknown. The Antarctic sea-ice regime is largely seasonal, and thus, its surface roughness characteristics might exhibit large interannual variability. In situ observations reveal that Antarctic multiyear ice and summertime first-year sea ice exhibit the greatest surface roughness, nearly three times that of first-year ice in autumn[180]. These seasonal differences in surface roughness might exceed regional differences[180]. Although Antarctic sea ice is considerably smoother than Arctic sea ice[181], the sea-ice surface roughness in both hemispheres is ultimately dependent on the same thing: the age of the sea ice and the floe's deformation history.

Polynyas. Polynyas are openings within the sea-ice pack that persist anywhere from a few days to several months and range from hundreds of metres to hundreds of kilometres in size[4,5,182]. Their presence promotes phytoplankton productivity[183–186], creates breathing holes and migration routes for marine mammals, and serves as a major feeding habitat for fish, birds and marine mammals[187,188]. The occurrence of polynyas depends on winds, ocean currents, tides and bathymetric features (such as seamounts) that can diverge the sea-ice pack, melt the sea ice or both[4,5,182]. Most polynyas form when strong winds advect sea ice away from the land, leaving open water next to coasts or landfast ice[189]. Others are caused by the upwelling of warm water[190]. Newly exposed open water and thin sea ice in polynyas are a major source of heat and moisture to the atmosphere above[191–193]. The large heat loss in these areas also facilitates the rapid growth of sea ice, which is a key mechanism for deepwater formation and ventilation[194–197].

In the Arctic, the passive microwave satellite record shows that the occurrence of wintertime (December–March) polynyas has increased by 1.4 days per decade (1979–2023). Within this trend, strong latitudinal differences are evident (Fig. 5c). North of 59° N, the increase is ~2.4 days per decade and is primarily driven by the increased persistence of the North Water polynya in Baffin Bay and, to a lesser extent, coastal polynyas near Franz Josef Land and Hudson Strait. South of 59° N, polynya occurrence has decreased by ~1.6 days per decade over the same period. This decrease is predominantly caused by the reduced persistence of the Gulf of St Lawrence polynya, which typically forms as a result of strong winds and the upwelling of warm seawater[198]. Although no substantial change in polynya occurrence was observed in the Sea of Okhotsk, ice production in the region decreased by 11.4% ± 10.4% over 1988–2008[199]. This decrease was attributed to warm autumn air temperatures, which slowed the advance of the sea-ice cover[199].

In the Antarctic, the mean polynya occurrence over the annual cycle increased by 0.7 days per decade during 1979–2023. However, as in the Arctic, the trends in Antarctic polynya occurrence show large regional differences (Fig. 5d). The most persistent polynyas occur in eastern longitudes[200], where these features have become longer lasting and larger[201]. In particular, polynyas in the coastal sector of the eastern Indian Ocean have increased in persistence by ~3.2 days per decade over 1979–2023. By contrast, polynya occurrence has decreased by ~2.2 days per decade in the Amundsen and Bellingshausen sector, where a decreasing trend in polynya area has also been observed (1979–2022) and attributed to long-term sea-ice loss[201].

Among all Antarctic polynyas, those with the highest ice production rates are found in the Ross Ice Shelf polynya region[202]. There, polynya persistence has declined by ~0.5 days per decade over 1979–2023, which is consistent with the observed reduction in polynya area and the ~30% overall decrease in ice production in March–October (1992–2005)[202]. Of note, polynya areas in the Ross sector can exhibit a cyclical, multiyear pattern that is related to the Amundsen Sea Low and Southern Annular Mode[201]. Although the change in its occurrence over 1979–2023 is not statistically significant, the Weddell polynya intermittently re-emerged in the 2010s, which might be linked to the Southern Annular Mode[203]. Even so, the Weddell polynya was considerably smaller in the 2010s than it was in the 1970s[204].

The future sea-ice environment

Sea-ice changes are influenced by a variety of dynamic and thermodynamic processes that involve multiple elements, from the ocean to the atmosphere, and operate across different time-scales. The key atmosphere–ice–ocean processes involved predominantly occur at high latitudes, where the most pronounced climatic changes have been observed and are projected to continue. As a central component of polar environments involved in numerous feedback processes[37], sea ice is expected to undergo substantial transformations in the coming decades.

Here, we discuss the current state of knowledge on projected changes in Arctic and Antarctic sea-ice properties and processes (Fig. 6). A recurring theme in this discussion is that the knowledge of projected changes in sea-ice properties and processes is acutely limited compared with that of sea-ice coverage. One reason for this disparity is that future changes are estimated using climate models, which cannot account for all sea-ice properties and processes nor, in many cases, for their time-evolving aspects (such as the evolution of sea-ice density). These limitations arise from several factors, including model design constraints (for example, most sea-ice models lack parameterizations for landfast ice formation such as grounding or anchoring at icebergs), computational constraints, insufficient spatial resolution (for example, the accurate representation of polynyas requires detailed modelling of coastal and katabatic winds) and/or inconsistencies in observations that, in turn, affect the assessment of model results.

Hemispheric sea-ice extent and area remain the two main diagnostics for evaluating the evolution of the Arctic and Antarctic sea-ice states in model projections[15,205]. On large spatial and temporal scales, the extent

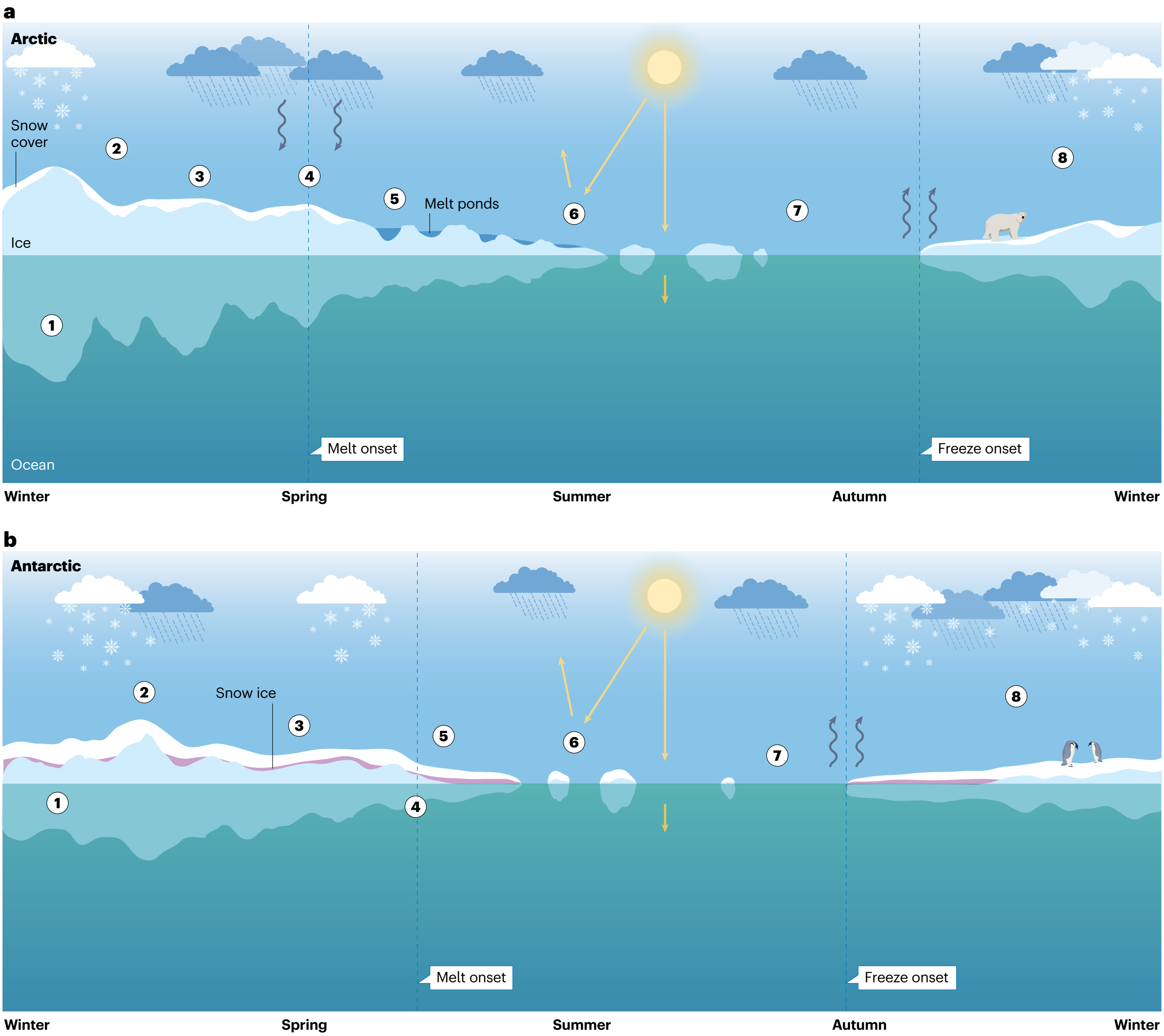

Fig. 6 | Possible future sea-ice properties and processes of the Arctic and Antarctic environments. a,**b**, Arctic (**a**) and Antarctic (**b**) sea-ice properties. (1) Sea ice is expected to become thinner in both hemispheres with the shift to a seasonal ice regime in the Arctic and an increasingly shorter sea-ice growth season in the Antarctic. Thinner sea ice is more responsive to wind and ocean forcing, which results in a more dynamic, less-consolidated sea-ice cover. (2) The sea-ice covers in both hemispheres might become smoother over time with the loss of hummocky, multiyear ice. Smoother sea ice modifies the energy exchange between the atmosphere and ocean, as well as the distribution of snow and melt ponds on its surface. (3) The snow covers of both sea-ice environments are likely to thin, owing to later sea-ice formation in the Arctic (that is, after the time of peak snowfall) and, in the Antarctic, the possibility of increased snow-ice formation due to the thinner sea-ice cover. Thinner snow enables sea ice to thicken quickly during the autumn via a negative feedback. However, thinner snow would also enable increased amounts of solar radiation to penetrate the sea-ice covers and underlying ocean earlier in spring, resulting in a positive feedback. (4) Melt onset is predicted to occur earlier in both hemispheres. In the Arctic, earlier surface melt would hasten sea-ice melt through a positive albedo feedback. In the Antarctic, earlier bottom melt could enhance flooding. (5) More extensive melt ponding might occur in the Arctic as a result of the reduction in hummocky, perennial ice, which would hasten surface, internal and bottom ice melt and lead to floe degradation. In the Antarctic, if air temperatures are sufficiently warm, flooding and bottom melt could promote internal melting of the sea-ice cover until floes disintegrate. (6) Sea ice in both hemispheres is expected to develop lower surface albedo in summer, which would increase light levels and solar heating in the upper ocean and cause subsequent ecosystem shifts and disruptions. (7) The duration of open-water season is predicted to increase in both hemispheres, leading to increased wave action, coastal erosion and solar heating of the ocean. In the Arctic, later freeze-up of the sea ice is expected to be the primary contributor to the lengthening of the open-water season. In the Antarctic, it is uncertain how the timing of melt and freeze onset will change. (8) In both hemispheres, precipitation cycles are likely to shift and contain more rainfall throughout the sea-ice growth season, which would contribute to a vertically more complex snowpack on Arctic and Antarctic sea ice.

of Arctic sea ice is tightly linked to climate forcing, be it the global mean surface temperature, cumulative CO_2 emissions or atmospheric CO_2 concentrations. The relationships of Antarctic sea-ice extent and area with large-scale radiative and temperature forcing are less evident. Moreover, these diagnostics have limited utility for understanding regional and seasonal changes and the context in which these changes occur because the energy exchange between the atmosphere, sea ice and ocean is both modulated by and driven by sea-ice properties and processes.

Future sea-ice age and thickness

As sea-ice loss continues into the twenty-first century, sea ice is expected to become increasingly thinner and younger (Fig. 6). Few studies have focused on projections of sea-ice thickness, and at the time of writing, no studies have evaluated projections in sea-ice age for either the Arctic or Antarctic. Although some climate models project that the mean September sea-ice thickness will be <0.5 m in the Arctic by the end of the twenty-first century[206,207], several CMIP3 and CMIP5 model simulations show thick sea ice in regions where thick ice is not observed[208,209]. Given the large inter-model spread and critical role of sea-ice thickness in sea-ice survivability, efforts are needed to develop observation-based diagnostics of sea-ice thickness to help pinpoint model deficiencies.

Future sea-ice thermodynamics

In the Arctic, climate models project that the retreat of sea ice will continue year-round and ultimately lead to ice-free conditions[15,210]. A direct consequence of this retreat is that, for many locations in the Arctic Ocean, sea-ice melt will occur earlier[211], freeze-up will occur later[212], and the duration of the open-water season will lengthen[213–215] (Fig. 6). The projected increase in the open-water season is dominated by delayed freeze-up rather than earlier ice melt[212,216,217], although there is large inter-model spread in freeze-up dates, which is attributable to model differences[211]. At the time of writing, no equivalent analysis has been performed on the future seasonality and melt season characteristics of Antarctic sea ice, owing to the relatively larger model uncertainties and inter-model spread[205]. Even so, CMIP6 shows modest improvements in simulations of monthly Antarctic sea-ice coverage, relative to comparisons with observations and CMIP5 simulations[205].

The future of snow on sea ice is dictated by competing factors, such as air temperature (which controls the vapour-holding capacity of the air through the Clausius–Clapeyron relationship), the eventual phase of precipitation (liquid or solid), poleward atmospheric moisture transport[218], and the presence or absence of sea ice as a platform for snow accumulation. Although the interaction between these factors is complex, model projections generally agree that, despite a projected increase in snowfall, snow depth on Arctic sea ice will decrease through the twenty-first century (Fig. 6) as a consequence of delayed freeze-up[219–222]. Of note, CMIP6 simulations exhibit a large inter-model spread in projected snow depth trends[223]. Snow is expected to have an increasing influence on the Arctic sea-ice mass budget in the future, as thin sea ice is more thermodynamically sensitive to the presence of an overlying snow cover compared with thick sea ice[1]. Future snow loss and the associated increases in under-ice light levels are also expected to have repercussions for the Arctic marine ecosystem[224]. For the Antarctic, projections of snow on sea ice have not yet been examined. However, CMIP6 models show that snow-ice formation is an important source of uncertainty in the evolution of the Antarctic sea-ice mass balance, as the inter-model spread can be as large as the multi-model mean signal[225].

The future state of other key thermodynamic features, such as sea-ice albedo and melt pond coverage, have undergone limited study[226,227]. According to 30 ensemble members from the Community Earth System Model (CESM), the June surface albedo in the Arctic is projected to decrease by 1% per decade over 1920–2080 under the Representative Concentration Pathway (RCP) 8.5 forcing scenario as a result of earlier melt onset, longer snow-free conditions and increased melt ponding[227] (Fig. 6). As projected sea-ice loss continues into the twenty-first century, the effects of increased open ocean on solar absorption surpass those resulting from the changes in the state of the sea-ice surface[227]. CMIP5 and CMIP6 models also show a projected decrease in Arctic surface albedo, albeit with large inter-model spread attributed to model differences[227–229] particularly with regard to the treatment of sea-ice properties and processes (for example, implicit versus explicit melt ponding[226]). So far, no equivalent study has been conducted on surface albedo projections of Antarctic sea ice.

Future sea-ice dynamics

As sea ice continues to thin, climate model projections suggest that the trend for increased winter Arctic sea-ice drift will continue throughout the twenty-first century[230], but the summer drift of Arctic sea ice will decrease. Although the winter trends can be confidently attributed to wind stress and internal stress terms that counteract changes in the surface tilt force, the factors causing the decreasing summer trends are less clear and might be related to smoother sea ice. The decreasing trend in summer sea-ice drift could be linked to the projected increase in sea surface height over the Arctic Ocean[230]. However, the increasing trend in summer ice drift measured by buoys is not captured by climate models[231,232], which highlights the caution needed in the interpretation of projected summer trends. To our knowledge, no analysis of projected sea-ice drift exists for Antarctic sea ice. The relationship between projected drift and projected sea-ice roughness is also absent from the literature and is a topic for future study.

In relation to polynyas, the future holds considerable uncertainty because the localized processes that influence polynya behaviour are not included in many climate models. In the Antarctic, only half of 27 CMIP6 models simulate off-shore polynyas, and the areas of these polynyas are largely underestimated[233]. For coastal Antarctic polynyas, the simulated areas vary by at least a factor of 2.5, with these differences attributed to model resolution[233]. Scrutiny of the model resolution, physics, component couplings and methodology of polynya identification is crucial for appropriate model interpretation. In an analysis of 25 ensemble members, CESM2 projects a substantial decrease in polynya frequency in the Ross Sea into the late twenty-first century under the shared socioeconomic pathway (SSP) 3.0–7.0 forcing scenario[234]. The westward shift and deepening of the Amundsen Sea Low weakens winds and reduces ice export out of the Ross Sea, whereas local shoaling of the ocean mixing layer reduces ocean heat flux. Collectively, these processes facilitate a more stable ice cover and thus reduced occurrence of polynyas in the model simulations[234]. The CESM2 results underscore the importance of examining local atmosphere–ice–ocean feedback processes, which could shed light on future polynya occurrence.

Summary and future perspectives

At the time of writing, the ramp-up of observational activities leading to the 5th International Polar Year (IPY) in 2032–2033 presents a tremendous opportunity for coordinated observations of the Arctic and Antarctic sea-ice environments. In this regard, now is a crucial time to consider what is needed in sea-ice research, immediately and in the future. Here, we provide an overview of the known changes in Arctic and Antarctic sea ice, major knowledge gaps and recommendations for future sea-ice research that could advance knowledge and predictive capabilities of sea ice and its role in Earth's changing climate.

In summary, profound changes have occurred in the state of the Arctic sea-ice cover in response to anthropogenic climate change. Arctic sea ice is now less extensive, younger, thinner, less reflective and has a thinner snow cover owing to the lengthening of the sea-ice melt season. As a result of sea-ice thinning, the Arctic sea-ice cover is more dynamic and drifts at higher velocities than in the 1980s. Collectively, these structural and dynamic changes modify air–sea exchange, ocean stratification and large-scale atmospheric circulation, which collectively exert strong influences on the global climate system. Notably, regional differences are evident in the long-term changes in Arctic sea-ice conditions, as exemplified by polynyas. Some regions (such as Baffin Bay) have exhibited more-frequent polynya openings, whereas others (such as the Gulf of St Lawrence) have exhibited less-frequent polynya openings over the past four decades. These regional differences point to the need for improved understanding of the geographically dominant interactions between the atmosphere, sea ice, ocean and ecosystem and their subsequent impacts on local-to-global scales.

In the Antarctic, the long-term changes in sea-ice properties and processes are less clear because of limited in situ observations, large uncertainties in satellite retrievals of specific variables and considerable regional differences in dominant atmosphere–ice–ocean interactions. The Antarctic sea-ice extent, age and thickness show large year-to-year variability. In addition, for some properties (such as sea-ice thickness), uncertainties in the retrievals and the resulting differences between retrieval algorithms exceed the magnitude of estimated trends. The timing of melt onset in the Antarctic has exhibited no substantial change, nor has snow accumulation in the Weddell Sea. The long-term changes in surface albedo are regionally distinct and can be attributed to areal changes in sea-ice coverage. Although Antarctic sea-ice dynamics remain insufficiently constrained by observations, there is a need to improve estimates of sea-ice deformation, divergence and wind-driven redistribution, as sea-ice dynamics govern both the thickness distribution and seasonal persistence of Antarctic sea ice.

Considering the strong regional variability of Antarctic sea-ice trends and their drivers, attention should be focused on key locations that can help resolve how different sea-ice properties and processes respond to and modulate regional differences in atmosphere and ocean forcing. For example, the Weddell Sea is the primary origin of Antarctic perennial ice and exerts a disproportionate influence on the summer extent of circumpolar sea ice. Variability and trends in this region strongly modulate the state of Antarctic sea ice, which as a result has a strong influence on deepwater formation and the global overturning circulation. Over 2022–2025, the Weddell Sea has experienced pronounced anomalies, including record lows in sea-ice extent, changes in ice drift and deformation patterns, and shifts in atmosphere–ocean forcing, which challenge the previous perception of relative stability in this sector. The Ross Sea, by contrast, has exhibited the largest variability in winter ice extent, and the Amundsen, Bellingshausen and eastern Ross Seas have intermittently experienced a near-complete loss of summer sea ice. Improved observational coverage and understanding of the dominant processes in these often-contrasting regions are essential for constraining Antarctic-wide trends and improving the predictive capability of climate models.

The marked loss of global sea ice has wide-ranging socioeconomic consequences, from coastal erosion in Arctic communities to global impacts on food security[19]. Although CMIP6 models point towards the continued loss of sea ice, the large inter-model spread in the rate of sea-ice loss is indicative of the large uncertainties present in near-future and far-future projections. These uncertainties manifest in the even larger inter-model spread of projected sea-ice properties and processes. Reducing these uncertainties requires strategic alignment between observational priorities and model development so that societies can be in a stronger position of preparedness for future environmental changes. Practical constraints preclude the direct observation of all sea-ice properties and processes to the level of detail needed for perfect climate model simulations. Therefore, we recommend the prioritization of observations of sea-ice variables that are expected to change now and in the coming decades and that can inform how the climate system responds to both natural climate variability and anthropogenic climate change. Although all sea-ice properties and processes could be considered of crucial importance from different viewpoints, from the perspective of understanding Earth's climate, the utmost priority should be assigned to sea-ice thickness and surface albedo and the sea-ice characteristics that are vital to the interpretation of their spatiotemporal patterns.

Sea-ice thickness is a promising metric for the evaluation of climate model projections, as the ability of climate models to capture the springtime distribution of sea-ice thickness is strongly related to their ability to reasonably predict the area of sea-ice loss in summer[235–237]. Furthermore, climate models that exhibit a strong relationship between the spring sea-ice thickness and summer area of sea-ice loss show a smaller spread in projected sea-ice loss[238,239]. Thus, there is strong motivation to advance sea-ice thickness model-observation assessments, as reliable projections of sea-ice thickness are informative for shipping, ecosystem disruption and other socioeconomic factors. To enable robust model assessments focused on sea-ice thickness, progress in the following activities is required: a comprehensive uncertainty quantification and evaluation of existing sea-ice thickness products; dedicated validation programmes to advance knowledge of complex snow and sea-ice conditions and constrain retrieval uncertainties[78,135,240]; investigations of the influence of snow on the sea-ice mass budget; and the development of a standardized time-series of sea-ice thickness for both poles, with particular attention to inter-satellite sensor calibration.

In both hemispheres, surface albedo is an indicator and amplifier of anthropogenic climate change. This variable is a useful metric for evaluating the strength of the ice–albedo feedback in climate models and for identifying deficiencies in model physics[229,241]. Moreover, surface albedo might become as promising a metric as sea-ice thickness for improving sea-ice predictions using data assimilation[242]. Unlike the sea-ice thickness record, stable satellite records exist of surface albedo for both hemispheres (as exemplified herein[243]). Yet, uncertainty quantification of satellite-derived albedo estimates is limited by the disparate, point-scale nature of in situ observations over sea ice. Unknown uncertainties reduce the utility of satellite-based products for assessment of climate models and data assimilation in forecast models, which hinders the pathways to more-reliable predictions. Therefore, we recommend the gathering, standardized processing and synthesis of existing in situ observations to enable robust uncertainty quantification of satellite retrievals, whether they are of surface albedo or any other sea-ice properties that are sparsely sampled, such as snow depth. Of similar value are high spatial resolution retrievals of sea-ice properties from airborne and spaceborne sensors, which, when compiled and processed in a consistent way, can provide a vital bridge between in situ point measurements and coarser resolution satellite products.

The prioritization of sea-ice observations could also be aided by model sensitivity studies, which help to determine the level of detail needed for representing sea-ice properties in process, forecast and climate models. For instance, a sensitivity study on the effects of different treatments of the sea-ice surface state (such as implicit versus explicit snow or melt ponds) on albedo feedbacks could help determine which types of sampling (such as temporal or spatial) and field measurements (including snow depth and melt pond albedo) are required to improve specific model physics. Moreover, sensitivity studies can help to reveal the importance of both positive and negative feedback mechanisms associated with changing sea-ice properties. This information, in turn, can inform the experimental design of observational programmes, such as those in the upcoming 5th IPY, and thereby maximize their scientific return.

The different geographical makeups of the Arctic and Antarctic result in atmosphere–ice–ocean interactions that are unique to each environment. These distinct atmosphere–ice–ocean interactions consequently affect which sea-ice processes dominate. As a result, Arctic sea ice is expected to respond differently to anthropogenic climate change compared with Antarctic sea ice. Improved understanding is needed of the mechanisms that contribute to the hemispheric differences in sea-ice properties, how those relationships evolve in response to natural climate variability and anthropogenic climate change, and the impacts of changing sea-ice properties on the energy exchange within the polar and global climate systems. New knowledge in these areas can be achieved through joint observational and modelling efforts that inform and are informed by bipolar observation programmes. Such programmes that carry out standardized observables are essential for pinpointing regional-to-hemispheric differences in sea-ice properties and their roles in atmosphere–ice–ocean–ecosystem interactions.

Other major knowledge gaps include the relationships of changing sea-ice conditions to other parts of the cryosphere (such as ice shelf stability) and other Earth system components (such as the ecosystem). These knowledge gaps can be remedied through tightly coordinated, interdisciplinary field studies that focus on process-oriented interactions between system components and support model development, as was done for the 2019–2020 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition[244]. In this regard, it is the act of bringing disciplinary components together at the earliest planning stage that leads to interdisciplinary science questions that can be realistically addressed by a field programme. The scientific success of such coordination relies on advanced and inclusive planning, standardized observation protocols and adherence to open science principles before, during and after data collection. All these aspects greatly increase the scientific, operational and community return on investments.

Lastly, it is prudent to consider which sea-ice properties and processes we will have no or limited access to in the future, yet, if the measurements were collected within the next 5 years, could greatly benefit research and policy decisions in the coming decades. Therefore, thoughts of the future underpin the international collaboration necessary for advancing sea-ice research today. In light of the upcoming 5th IPY, the timing is perfect for making major advances in sea-ice research that could have global consequence.

Data availability

Data discussed in this Review are available from the following references and websites: bootstrap sea-ice concentrations[245]; National Aeronautics and Space Administration (NASA) Arctic Sea Ice Melt: melt onset and freeze-up dates[11]; snow depth[246,247]; The Cold Regions Research and Engineering Laboratory (CRREL)-Dartmouth Mass Balance Buoy Program; snow buoy data and processing[136,137], PANGAEA; National Snow and Ice Data Center (NSIDC) snow radar data; ICESat-2 and CrySat-2 snow depth[248]; surface albedo[243]; Arctic sea-ice age[249] and sea-ice motion[250]; National Oceanic and Atmospheric Administration/NSIDC Climate Data Records sea-ice concentrations for polynyas[251].

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Author contributions

M.A.W. led the conception, data collection, analysis, writing and editing of the manuscript before submission. S.A., A.B., S.K. and A.R. performed data collection and analysis. T.M., F.M. and T.T. made contributions to the content and literature review. All authors contributed to the discussion of Figs. 1–6 and writing and editing the manuscript.

Competing interests

The authors declare no competing interests.

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