Changes in Arctic and Antarctic sea-ice properties and processes

Melinda A. Webster[1,†], Stefanie Arndt[2], Angela Bliss[3], Sahra Kacimi[4], Ted Maksym[5], François Massonnet[6], Aku Riihelä[7], and Takenobu Toyota[8]

[1]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.
[2]Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, University of Hamburg, Hamburg, Germany
[3]Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
[5]Woods Hole Oceanographic Institution, Woods Hole, MA, USA
[6]Earth and Climate Center, Earth and Life Institute, Université Catholique de Louvain, Belgium
[7]Meteorological Research, Finnish Meteorological Institute, Helsinki, Finland
[8]Institute of Low Temperature Science, Hokkaido University, Hokkaido, Japan

[†]e-mail: melindaw@uw.edu

Abstract | Although sea ice covers ~9% of the world's oceans, its presence, and absence, vastly alter the energetic balance of Earth's climate. Because of geographic differences, Arctic and Antarctic sea ice have different dominant properties and processes, which produce different responses to natural variability and anthropogenic change. In this Review, we survey changes in sea-ice properties and processes of the Arctic and Antarctic environments. In the Arctic, the melt season has lengthened by ~7.4 days decade^{-1} (1979-2024). There has been a corresponding decrease in winter sea-ice thickness (1.6 m mean total over 1980-2023), summer surface albedo (0.03 decade^{-1} over 1979-2020), and spring snow depth (2.5 cm decade^{-1} over 1954-2024). In comparison, corresponding changes in the Antarctic are small overall due to contrasting regional and temporal trends. From a dynamic perspective, sea-ice motion in both hemispheres has increased, with 0.63 cm s^{-1} decade^{-1} in the Arctic (1978-2024) and 0.69 cm s^{-1} decade^{-1} in the Antarctic (1982-2024), whereas trends in polynya occurrence differ by region. Future research should prioritize sea-ice observations that can inform how the climate system responds to natural variability and anthropogenic change, be standardized to increase uptake by the broader scientific community, and target process-oriented interactions to support model development.

Introduction

Despite being a thin (<3 m mean) veneer on the ocean, sea ice plays an outsized role in Earth's climate. 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[4,5], produces bottom water masses that form the lower limb of the ocean's thermohaline circulation. Seasonal sea-ice melt drives the redistribution of freshwater and stratifies the upper ocean, which strongly influences the phenology of primary productivity and the polar marine ecosystem[6].

Since the late 1970s, satellite observations have recorded dramatic changes over the ice-covered oceans (**Fig. 1**). Arctic sea-ice extent in September has declined by 14% decade^{-1} over 1979-2024[7]. In addition to this loss, Arctic sea ice has shifted from a perennial to a seasonal ice regime[8,9,10] and continues to experience an increasingly prolonged melt season[11,12,13]. Current model projections suggest that a seasonally ice-free Arctic — defined as 1 million km^2 sea-ice area in the summer — is likely imminent by 2050, or even as soon as 2035, owing to positive feedbacks that enhance sea-ice loss[14,15,16]. This critical point will carry significant environmental, geopolitical, economic, and societal consequences[17,18,19]. In the Antarctic, annual sea-ice extent has exhibited no significant circumpolar change (1979-2024), but there is a marked increase in its interannual variability, with extremes shifting from record maximum extent in 2014 to record low extent in 2023 (**Fig. 1**). In particular, record lows in summertime sea-ice extent occurred over the last four consecutive years (2022-2025)[20,21,22].

While satellite sea-ice extent represents the longest continuous record of sea-ice observations, it is a limited metric of polar climate change. There are several unknowns arising from the increasing variability in sea-ice coverage, such as temperature and cloud feedbacks[23,24], ocean heat exchange[25], and midlatitude connections[26], which points to a need for a more comprehensive understanding of changing sea-ice properties and processes. Additional descriptors of the changing state of the sea-ice system, like sea-ice thickness, snow depth, and surface albedo, have gained interest in climate monitoring and prediction, as they help constrain feedbacks and disentangle natural versus anthropogenic climate change. For instance, knowledge of sea-ice thickness is critical to support process studies and seasonal forecasts, as thickness integrates both the thermodynamic and dynamic processes that control sea-ice growth and decay. As such, sea-ice thickness is expected to decrease more strongly than sea-ice extent in the Arctic in response to warming[27], making it a valuable marker forestalling the effects of a changing Arctic sea-ice system on the global climate.

In this review, we go beyond trends in sea-ice coverage to summarize how sea-ice properties and processes have changed in response to climate change and variability. We provide a broad summary of sea-ice changes that complements the long-term record of sea-ice coverage. We bring together results of changing Arctic and Antarctic thermodynamic and dynamic properties and processes, including sea-ice age, thickness, sea-ice season and melt season characteristics, snow depth, albedo, motion, surface roughness, and polynyas. We discuss the potential impacts of their changes on key atmosphere-ice-ocean feedbacks and end with an outlook on critical knowledge gaps and the joint model-observational priorities that can help lead to a more holistic understanding of the sea-ice systems and their role in global climate.

The Arctic and Antarctic sea-ice environments

Most differences between Arctic and Antarctic sea ice (**Fig. 2**), the dominant drivers of their variability, and their response to climate change are determined by geography. The high Arctic Ocean is almost entirely confined by land (**Fig. 1**). The land restricts sea-ice export and largely insulates the Arctic ice pack from the impact 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, driven by the Beaufort High[28]. The 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 Archipelago and serves as the primary egress for Arctic sea ice through Fram Strait. This confinement allows sea ice to persist in the central Arctic for many years, reaching a mean thickness of several meters[8,29].

Freshwater from Arctic rivers is similarly confined, contributing to strong stratification that restricts deep ocean heat from reaching the ice underside[30], thereby permitting ice to grow thermodynamically much thicker than Antarctic sea ice (**Fig. 2**). The Arctic peripheral seas, in contrast, are exposed to the open ocean, frequent storms, and warmer waters, so that 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 sea-ice pack is unconstrained by land (**Fig. 1**). There, it 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 is weakly stratified, in part, due to the northward export of surface freshwater content[32], so that upward ocean heat flux from the warmer, deeper waters limits winter sea-ice growth[33] . Together, these forces create a dynamic ice pack, with more open water and leads, thinner ice, and relatively deeper snow than its Arctic cousin (**Fig. 2**). The deeper snow, divergent ice cover, and exposure to warm upper ocean drive rapid summer melt predominantly at the ice underside, with weaker surface melt, and comparatively little sea ice surviving the melt season. However, sea ice near the continental margins may grow many meters thick from being compressed against the shore. Buried under heavy snowfall and sheltered by the coast, this ice can persist through summer.

The differences in Arctic and Antarctic geography mediate the impact of both internal and forced climate variability on sea-ice variability and change. That polar amplification of anthropogenic warming is much stronger in the Arctic than the Southern Ocean has long been known[34]. Both the influence of ocean heat uptake in the vast Southern Ocean[35,36] and differences in the strength of atmospheric feedbacks[37] contribute to the contrasting response. Natural climate variability has a larger influence in the Antarctic, with strong teleconnections between tropical variability (particularly El Niño, Southern Oscillation) and storm tracks that ring the Antarctic[26]. These teleconnections may 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 include both the nature of the processes that govern Arctic and Antarctic sea-ice characteristics and in how geography modulates the atmospheric and oceanic forcing that the sea-ice covers experience.

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, age and thickness are intricately linked and arise from the interplay between thermodynamic and dynamic processes. The next section reviews the importance of sea-ice age and thickness in the climate system, the decreasing trends in the Arctic, and notably high variability in the Antarctic. All trends reported in this review are at least 95% statistically significant unless otherwise noted (**Table 1**).

Sea-ice age

The age of sea ice strongly impacts 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[42], providing a freshwater source for Arctic coastal communities[43]and making the ice mechanically stronger[42]. The older the sea ice is, the rougher and thicker it tends to be from 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 ice regimes in the Arctic and Antarctic. When a sea-ice floe survives its first summer melt season, it becomes perennial (old) ice, whereas if it survives two melt seasons, it is considered multiyear ice[48].

Since 1984, there has been an unprecedented shift towards a seasonal ice regime in the Arctic[10,49] (**Fig. 3a**). The area of sea ice at least 3 years old in March, the month with the largest ice area, decreased by 0.74% decade^{-1} over 1984-2024. This loss was accompanied by a corresponding increase (0.63% decade^{-1}) in first-year and younger ice. 2007 was an exceptional year of 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 sectors, while the remaining perennial ice persists in the central Arctic[10]. Perennial ice is now younger, with two-to-three-year-old ice making up more than 50% of the perennial ice cover in 2013-2023, compared to 25% in 1990-2000. The loss of perennial ice has contributed to atmospheric warming[50,51,52]. and disrupted the regular functioning of the Arctic marine ecosystem. Seasonal ice is less favorable for sympagic phytoplankton species and grazers[53,54] and is less stable for marine mammal haul-outs[6]. As perennial ice loss continues, it is having profound effects on the Arctic coastal communities, ecosystem, and climate system.

In the Antarctic, there is considerably less perennial ice than in the Arctic, and the perennial ice that does exist tends to be comparatively younger. Perennial snow and the lack of sustained surface melt make reliable identification of Antarctic ice age difficult with remote sensing methods; there is no comparable record of ice age in the Antarctic[55]. While the western Weddell Sea consistently has perennial ice, other 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 increasingly less present in the 2010s[56,57,58]. Active and passive microwave satellite retrievals suggest no significant trends in perennial ice in April-November over 2013-2023, with the time-series being marked by high interannual variability[55]. The time-series of the annual minimum sea-ice area, a proxy for perennial ice area, exemplifies this high interannual variability (**Fig. 3b**). Similar high variability has been observed for perennial landfast ice, the duration of which depends on bathymetry, grounded tabular icebergs, and other local, geographic features that protect the ice from wind and ocean forcing[59].

Sea-ice thickness

Over long time-scales, the sea-ice thickness distribution integrates both the thermodynamic and dynamic responses of the sea-ice cover to atmospheric and oceanic forcings[60]. While 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. The thicker the sea ice is, the more resilient it is to summer melt, as more energy is needed to completely melt the ice. Knowledge of the ice thickness distribution and its variability are thus crucial for understanding sea-ice processes and informing predictions. Before the turn of the 21st century, sea-ice thickness monitoring in the Arctic was achieved by compiling ice draft measurements from submarine-based upward-looking sonars[61,62]. Satellite altimetry has transformed knowledge of sea-ice thickness by providing sea-ice thickness estimates at unprecedented spatial and temporal scales[63,64,65]. In particular, novel techniques based on the synergy of dual-band altimeter observations are opening new avenues for improved snow depth and sea-ice thickness estimates[66,67].

Within the submarine data release area, which covers ~38% of the Arctic Ocean, an average thinning of ~1.8 m occurred between 1958 and 2000[68]. Since then, three dedicated polar-orbiting altimetry missions have provided two decades of basin-wide coverage of Arctic sea-ice thickness. The combined time-series of submarine and satellite datasets (1975-2023) reveals that winter (fall) ice thickness now hovers around 2.0 m (1.3 m) from a peak of 3.6 m (2.7 m) in 1980[68] (**Fig. 3c**). The Arctic-wide thinning (0.6 m), 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 corresponds with the hiatus in declining sea-ice extent[69].

In the Antarctic, no comparable in situ time-series exists, as large-scale observations are sparse. To date, the most extensive compilation of Antarctic ice thickness remains the ASPeCt database[70], which contains observations from 83 voyages and 2 helicopter flights for 1980–2005 and was more recently updated to 2019[71]. Additional airborne surveys have provided valuable information on the interannual variability of ice thickness in the Weddell Sea[72]. Yet, these datasets offer a limited spatial and temporal view of Antarctic sea-ice thickness change. Satellite altimetry has made progress in mapping Antarctic sea-ice thickness[73,74,75,76], but, at the time of this writing, different retrievals exhibit inconsistent, long-term changes. For example, in the Weddell Sea, satellite sea-ice thickness estimates exhibit trends of opposing signs but are broadly consistent in the coastal regions of the Amundsen and Bellingshausen Seas[74–76]. Satellite retrievals of Antarctic ice thickness contain potentially large uncertainties[77] due to the complex nature of the Antarctic snow cover[78] and, thus, remain an active area of research. Although these satellite-based assessments differ in time periods, their differences underscore how the uncertainty in Antarctic sea-ice thickness retrievals is likely larger than the estimated trends[79]. Such uncertainty remains difficult to quantify, as it depends on the retrieval algorithm and assumptions or products used for snow properties (and their associated biases).

Thermodynamic Properties and Processes

Sea-ice thermodynamics describe the 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 length of the sea-ice season. Secondary factors include the state of the sea-ice surface, which can be bare, snow-covered, ponded, and optically-thin, all of which affect the surface albedo and solar absorption in the ice-ocean system. In this section, the nature of the Arctic and Antarctic sea-ice seasons and melt seasons, their snow covers, and surface albedo are presented. These characteristics are described within the context of known climatologies and observed changes.

Sea-ice season

The length of the sea-ice season provides a spatial perspective on the interplay between sea-ice growth and melt processes and, to a lesser extent, ice dynamics. The sea-ice season is defined as the total number of days that sea ice is present in a given area in a year. A shortening or lengthening of the sea-ice season has repercussions in the energy exchange between the atmosphere and ocean. A shorter sea-ice season facilitates atmospheric warming via enhanced air-sea heat exchange in autumn and winter[80] and ocean warming via greater solar absorption in spring and summer[81]. Thus, examining the sea-ice season length provides contextual information for understanding how Arctic and Antarctic sea ice are counteracting or amplifying feedbacks within the climate system.

Updating the analysis from Ref. [82], the Arctic sea-ice season length has dramatically shortened over 1979-2024 (**Fig. 4a**). For areas where the 1979-2024 average season length is 10 days or longer, the season has changed by -11.6 days decade^{-1}. The peripheral seas exhibited the largest decrease, with significant trends exceeding -60 days decade^{-1} in the northern Barents Sea and far northern Kara Sea, consistent with the trends reported by Ref. [82]. While Arctic sea-ice coverage has decreased in all months, the greatest loss has occurred in late summer and early autumn[83]. The decrease in the Arctic sea-ice season length is strongly related to the long-term changes in its melt season characteristics, the depth of its snow cover, and surface albedo, aspects of which are discussed below.

In contrast, changes in the Antarctic sea-ice season are more complex and regionally distinct (**Fig. 4b**). Updating the analysis from Ref. [84] to 1979-2024, there has been a strong reduction in the sea-ice season in the Amundsen and Ross Sea regions. The positive trends in the northern and western Ross Sea found by Ref. [84] have reduced to a smaller region of the western Ross Sea. Negative trends have also developed to the north of the Weddell Sea and spanning parts of the Indian Ocean and Western Pacific regions. The positive sea-ice season anomalies in the eastern Weddell Sea are new, developing since the 1979-1999 analysis by Ref. [84]. The trend for the entire Antarctic domain is -1.6 days decade^{-1} for 1979-2024 and, relative to the Arctic, is 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 influencing the length of the Antarctic sea-ice season.

Melt season characteristics

The onset of melt marks an inflection point in the seasonal cycle in which the mean sea-ice area and thickness begin decreasing. The Arctic and Antarctic melt seasons distinctly differ in their duration, intensity, and ice melt[85]. 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[86,87,88]. Arctic melt typically begins with freeze/thaw cycling within the snow layer, known as early melt onset. Following early melt onset, a period of sustained surface melt, known as continuous melt, begins[11]. The initiation of early and continuous melt onset precedes the dramatic albedo changes[3] associated with more advanced stages of surface melt, like melt ponding[89]. Under the ice, bottom melt starts at a similar time to surface melt with regional and interannual differences[90,91]. In contrast, Antarctic melt onset tends to start at the bottom of the ice, often from solar heat input in open water within the divergent ice pack or with advection of ice into warmer, more northerly waters[92,93,85]. Surface melt in the Antarctic is more muted relative to its Arctic counterpart[94,92]. Antarctic sea ice tends to melt primarily from the bottom-up and internally[95], while Arctic sea ice melts both from the top-down and bottom-up[90].

In the Arctic, high-frequency changes in passive microwave brightness temperatures are used to identify dates of surface melt onset, freeze onset and melt season length[11,96,97]. The Arctic melt season begins in late spring in the seasonal ice zone and progresses northward to the central Arctic by early summer[12,13]; however, significant trends in the Arctic melt season have occurred over 1979-2024[11]. North of 65°N, surface melt onset has trended earlier (~1.8 days decade^{-1}) and freeze-up has trended later (~5.6 days decade^{-1}), with an overall lengthening of the Arctic melt season by ~7.4 days decade^{-1} (**Fig. 4c**). Later freeze onset is occurring in all regions excluding the central Arctic[98], which is consistent with the observed patterns of Arctic sea-ice loss[99] (**Fig. 1**). In regions where earlier sea-ice retreat coincides with periods of high net radiation, sea surface temperatures have increased through an ice-albedo feedback[100,101], which has further delayed sea-ice freeze-up[102,99].

Unlike the Arctic, the melt season in the Antarctic is relatively short (shorter by ~one month) and rapid[85], yet, the Antarctic summer sea-ice retreat is larger, by 5 million square kilometers[58,83]. The majority (~39%) of surface melt occurs as diurnal freeze-thaw cycling, while less than 2% of melt events are continuous melt[103,104]. Accordingly, there have been no significant trends in ephemeral or continuous surface melt onset dates based on the passive microwave satellite record[104,105] (**Fig. 4d**). The high variability in surface melt onset dates[104,105,106] together with the record minimums in Antarctic sea-ice extent in 2022-2025[20,21,22] suggest that surface melt onset has little-to-no relationship with Antarctic sea-ice coverage. Rather, openings within the divergent Antarctic ice pack may allow sufficient solar absorption to cause a positive albedo feedback and rapid bottom and internal ice melt[92,93,107]. Additionally, ocean warming likely contributed to the recent record losses in Antarctic sea-ice coverage in 2022-2025[20,108].

Snow depth

Snow is one of the most reflective[109] and insulating[110,111], natural materials on Earth. These unique properties of snow, and the vast expanse of snow-covered regions, make snow a key component of the sea-ice and climate systems[112]. During the sunlit seasons, snow shields the sea-ice surface from solar radiation[2,3], reducing sea-ice melt and solar heating of the ice-ocean system[101]. Snow on sea ice is also a critical component of polar marine ecosystems, creating low-light conditions for sympagic algae[53,113] and vital denning habitat for marine mammals[114,115]. Although sea-ice growth is inhibited by the presence of snow[116,117], sometimes, the weight of the snow cover depresses the sea-ice surface below sea level, flooding the base of the snowpack. Upon freezing, the resultant snow-ice provides a positive mass contribution to sea ice[118]. Thus, snow and sea-ice conditions are intricately linked in a number of ways[44,119].

In the central Arctic, the best evidence suggests spring snow cover has thinned by -2.5 cm decade^{-1} 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[120]. There, the loss of perennial ice[40,8] and later freeze-up[11] has reduced snow accumulation in September-November, the peak in the snowfall cycle[120]. In contrast, snow depth in the Lincoln Sea and Fram Strait has had no significant change, which may in part be due to the proximity of the

North Atlantic storm track[121,122,123], which brings frequent, heavy snowfall, resulting high year-to-year snow depth variability[124,125].

Although the 1954-2013 snow accumulation time-series in the central Arctic suggests no significant change in snowfall[120], the 1980-2016 precipitation time-series shows an increasing proportion of precipitation is coming in the form of rain[126]. As a consequence, there have been more rain-on-snow events, trending 4-6 days decade^{-1} earlier in spring (1980-2017); these events might contribute to a 0.5 cm decade^{-1} thinning of the spring snow cover[127], which has important implications for surface albedo and subsequent melt rates. In the Arctic, most snow melts away each summer[128,129,130], leading to the formation of melt ponds and lower albedo of the surface[45,131]. Hence, the maximum snow depth attained by spring governs the duration of a highly-reflective surface in summer, during peak insolation[125].

Unlike the Arctic, snow in the Antarctic tends to persist throughout the melt season, forming a high-albedo, perennial snowpack[118]. The greater snow load on thinner Antarctic sea ice facilitates widespread flooding and snow-ice formation, and salt wicking up into the snow[118,132,133]. 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 relative to Arctic snow, which poses considerable challenges for accurate remote sensing retrievals of Antarctic snow depth[134]. The time-series of Antarctic snow depth is substantially more limited due to limited remote sensing retrievals and the scarcity of in situ observations. Moreover, flooding and snow-ice formation complicate autonomous measurements by buoys[135], yielding cumulative snow accumulation rather than snow depth[136]. In the Weddell Sea, one of the more sampled regions by buoys, no significant trend has been observed in snow accumulation over 2013-2024 (**Fig. 4f**).

Advances in altimetry[73] and passive microwave[137] remote sensing are starting to reveal a more complete picture of snow's spatiotemporal patterns in the Antarctic. In the Ross Sea, where some of the thinnest snow occurs[73], passive microwave retrievals suggest that snow has thinned in all seasons over 2002-2020[137]. Other spaceborne observations have shown no trends due to their relatively short time-series. While these early glimpses from spaceborne measurements are promising for monitoring snow, they are subject to possibly large uncertainties, which highlights the need for surface-based validation and snow monitoring efforts.

Albedo

The ice-albedo feedback is one of the most consequential phenomena in Earth's changing climate. With diminishing sea-ice coverage, the reflective sea-ice cover is replaced by dark ocean, enhancing the absorption of solar radiation, which, in turn, can melt ice further. With sea-ice loss, the climate system gains energy through a positive feedback, and the planet warms[138,139,140,141]. Both the presence of sea ice[142,140] and the state of its surface (for example, snow-covered, ponded, bare) govern the surface albedo in the polar seas[3,143,144]. Thus, trends in albedo can be considered in two parts: 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. The modulation is considerable; at least half of variability in sea-ice albedo is 'masked' by cloud cover[141,145,146]. However, in terms of decadal trends in polar ice-albedo feedback, cloud-masking effects appear to vary much less than the surface albedo changes resulting from sea-ice coverage and property variation. For this reason, the focus here is on sea-ice surface albedo and its variability, though emphasizing that clouds are critically important in the energy budget of sea-ice regions.

In the Arctic, clear-sky albedo has decreased by 0.03 decade^{-1} over 1979-2020 (**Fig. 4g**). This decrease is predominantly driven by the reduction in Arctic sea-ice coverage. As such, the hiatus in Arctic sea-ice decline from 2007 to 2024[69] may result in a more muted trend in surface albedo over 2007-2024. Nonetheless, for 1979-2020, the largest albedo decrease (-0.05 decade^{-1}) has occurred in the Barents and Kara Seas, which spatially coincides with the largest increase in annual mean temperature in the Arctic, exceeding 1.25°C decade^{-1} (1979-2021)[147]. The Beaufort and Chukchi Seas also exhibited a large decrease in albedo (-0.04 decade^{-1}), which results from the feedback of perennial ice loss, a more widespread open ocean, more solar absorption, and enhanced ocean warming[100,101].

The central Arctic and Lincoln Sea exhibited the smallest albedo decrease (-0.02 decade^{-1}) owing to more continuous sea-ice coverage. In areas where ice concentrations remained 80% or greater, the detrended June-July albedo and fraction of ponded sea ice are strongly correlated (r = -0.77). Although melt pond coverage drives year-to-year anomalies in midsummer albedo, the magnitudes are collectively determined by the areal coverage and optical properties of snow, bare ice, and ponded ice. As shown in model simulations[148], early melt pond formation leads to a diminished late-summer sea-ice extent through a positive-albedo feedback. Furthermore, while natural climate variability has an important, yet diminishing role in governing the interannual changes in summer snow depth[125], emerging critical questions revolve around the future magnitude and phase of precipitation over the sea ice and its impact on surface albedo. CMIP6 model projections point towards a wetter and increasingly rain-dominated Arctic by the end of the century, with negative implications for the surface reflectivity of the remaining sea-ice cover[149].

Relative to the Arctic, the pan-Antarctic trends in clear-sky albedo are considerably more muted at 0.002 decade^{-1} (1979-2020) (**Fig. 4h**). The small trend is a result of the sea-ice surface state remaining relatively invariable due to a persistent snow cover and because of disparate trends between regions. For example, in the Bellingshausen and Amundsen Seas, the albedo has significantly decreased by 0.04 decade^{-1}. There, decreasing October-May sea-ice coverage has exposed more open ocean, thereby decreasing the surface albedo during the sunlit months. In contrast, the east Antarctic sectors exhibited a positive trend of 0.03 decade^{-1} (1979-2020), though the significance of the trend was limited to the northerly areas of the ice pack in 0-60°E longitudes. Because snow tends to persist throughout the Antarctic melt season[118] and melt onset dates have not changed[104,105], trends in Antarctic albedo are presumably 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 ocean. Sea ice moves in response to the winds and ocean currents, drifting in large-scale patterns shaped by low and high air pressures, ocean gyres, and land. Its motion brings about mechanical redistribution of the sea-ice cover, forming 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[150]. These dynamic features create variable undulations in the sea-ice surface, which 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 called polynyas, which serve as biological hotpots and sea-ice factories in the polar and sub-polar seas. This section presents the observed changes in sea-ice motion (drift), surface roughness, and polynyas.

Sea-ice motion

Sea-ice motion affects the momentum exchange between the atmosphere and ocean[151,152], sediment[153] and pollutant transport[154,155,156], and residence time of sea ice in polar regions[157]. Sea ice typically moves 4-5° from the geostrophic winds due to the Coriolis effect[158,159], with variations depending on the sea-ice thickness, internal stress and consolidation of the pack ice[160], atmospheric and ocean drag[161,162], speed and direction of the underlying ocean flow[151,152], and proximity to land[158]. Near the coast, the response of sea-ice motion to geostrophic winds is usually weaker[158], with shear zones often existing between the landfast and drifting pack ice. As sea ice seasonally evolves, the speed and direction of sea ice also evolve, with floes in marginal ice zones often undergoing free drift in summer[152]. Sea-ice motion also varies with atmospheric variability (for example, the Arctic Oscillation[159], Southern Annular Mode[163]), as surface winds are the dominant force behind sea-ice drift.

Much work has been done in characterizing the seasonal and climatological patterns, variability[159], and trends in Arctic sea-ice motion[160,164,165,166]. While the data and methods across studies differ, the trends show the same thing: the drift of Arctic sea ice has increased[160,164,165,166]. Buoy data show that Arctic ice drift has significantly increased by 0.74 cm s^{-1} $decade^{-1}$ in winter and 0.59 cm s^{-1} $decade^{-1}$ in summer over 1979-2009[165]. The increase in drift is attributed to kinematic processes that promote ice thinning and a mechanically weaker ice pack, with openings in the ice pack contributing to a positive ice-albedo feedback[165]. Others have attributed the increased drift solely to thinner sea ice[160,165] or a combination of that and stronger wind forcing[166], with regional variations in their influence.

Revisiting the passive microwave satellite record for 1978-2024, ice drift in February-March has increased by 0.63 cm s^{-1} $decade^{-1}$ (**Fig. 5a**). The spatial pattern of trends suggests a strengthening of the Beaufort Gyre circulation and Transpolar Drift Stream, which might lead to more dynamic 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} $decade^{-1}$) and Baffin Bay/Nares Strait (0.95 cm s^{-1} $decade^{-1}$), two major export gateways[167,168].

Relative to the Arctic, the understanding of patterns, trends, and variability in Antarctic ice motion is more limited due to scarcity of observations. Furthermore, the dynamic nature of an unbound ice edge creates large uncertainties in satellite retrievals of sea-ice motion. Thus, most time-series begin in 1982 or later, when passive microwave retrievals are more temporally frequent. These time-series show that large-scale ice motion largely influences the extent of the Antarctic ice pack, and the sea-ice motion itself is strongly affected by atmospheric variability[163,169,170]. Geostrophic winds alone explain ~60% of the variance in wintertime drift[169]. Antarctic ice motion during the 1992-2010[171] and 1982-2015[169] periods exhibited spatially variable trends and are related to the trends in the large-scale wind fields[169,171].

Over 1982-2024, the pan-Antarctic ice drift for September-October has significantly increased by 0.69 cm s^{-1} $decade^{-1}$ (**Fig. 5b**). The largest trends occur along the Antarctic ice edge (0.79 cm s^{-1} $decade^{-1}$), where the eastward ice drift is driven by westerly winds and the Antarctic Circumpolar Current[170]. Near the coast in the Indian Ocean, sea-ice drift has increased by 0.87 cm s^{-1} $decade^{-1}$, being driven by a 0.64 cm s^{-1} $decade^{-1}$ increase in the zonal, westward drift. In contrast, trends in the Ross Sea are dominated by northerly ice advection, with the drift exhibiting a significant increase of 0.52 cm s^{-1} $decade^{-1}$ (1982-2024). These results underscore the strong regional differences in atmospheric forcing and sea-ice response, which points to a need for better 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 regions[151,152, 161,162]. From a thermodynamic perspective, surface roughness affects the surface energy balance of the sea-ice system by influencing wind-driven snow redistribution[172] and, in the Arctic, melt pond coverage[45,46,173], which, in turn, modifies the surface albedo and sea-ice melt rates. Hence, surface roughness plays an important role in the polar climate system by modulating dynamic and thermodynamic processes year-round.

Since the 1980s, there has been an increasing prevalence of seasonal ice in the Arctic[8,10], and seasonal ice is typically smoother than perennial sea ice[174,175,176]. With the shift to a seasonal ice regime, the surface roughness characteristics of Arctic sea ice may be changing. Seasonal ice is mechanically weaker and therefore deforms more easily, which promotes the generation of roughness, but the resulting roughness features are typically smaller and less persistent than those formed in multiyear ice. In the Lincoln Sea, a region characterized by perennial ice, a stark decrease in both the mean ridge density (-2.33 n km decade^{-1}) and ridge height (-0.14 m decade^{-1}) has occurred over 2004-2023[176]. Upward-looking sonar in Fram Strait has also captured the marked reduction (52%) in thicker (4+ m), deformed ice since 2007[49]. For seasonal ice, the decreasing trend in surface roughness has been more muted. Airborne retrievals of ridge density, height, and spacing over seasonal ice show little change over 1993-2023 in the Transpolar Drift[176]. These results underscore the greater homogeneity of seasonal ice relative to perennial ice, as well as its high interannual variability. Seasonal ice deformation largely depends on synoptic events, which are sporadic in nature and result in high interannual variability[177,178].

In the Antarctic, the surface roughness characteristics of sea ice are under-studied. Consequently, it is unknown if decadal changes in roughness characteristics have occurred. The sea-ice regime is largely seasonal, and thus surface roughness characteristics may exhibit high inter-annual variability. In situ observations reveal that both Antarctic multiyear ice and summertime first-year sea ice exhibit the greatest surface roughness, nearly three times that of first-year ice in autumn[179]. The seasonal difference in surface roughness may exceed regional differences[179]. Although Antarctic sea ice is considerably smoother relative to Arctic sea ice[180], the sea ice surface roughness in both hemispheres is ultimately dependent on the same thing: the age of the ice and the floe's deformation history.

Polynyas

Polynyas are openings within the sea-ice pack, ranging from 100s of meters to 100s of kilometers in size, that persist anywhere from a few days to several months[4,5,181]. Their presence promotes phytoplankton productivity[182,183,184,185], creates breathing holes and migration routes for marine mammals, and serves as a major feeding habitat for fish, birds, and marine mammals[186,187]. The occurrence of polynyas depends on winds, ocean currents, tides, and bathymetric features (like seamounts), which can diverge the sea-ice pack, melt the sea ice, or a combination of the two[4,5,181]. Most polynyas form when strong winds advect sea ice away, leaving behind open water next to coasts or landfast ice[188]. Others form from warm, upwelled water[189]. The newly exposed open water and thin ice in polynyas are a major heat and moisture source to the cooler atmosphere above[190,191,192]. The large heat loss in these areas facilitates rapid sea-ice growth, which is a key mechanism for deepwater formation and ventilation[193,194,195,196].

In the Arctic, the occurrence of wintertime (December-March) polynyas has significantly increased by 1.4 days decade^{-1} based on the passive microwave satellite record (1979-2023). Within this trend, there are strong latitudinal differences (**Fig. 5c**). North of 59°N, the ~2.4 days decade^{-1} increase is primarily driven by the greater 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 significantly decreased by ~1.6 days decade^{-1}. The decrease is predominantly caused by less persistence in the Gulf of St. Lawrence polynya, which typically forms from strong winds and the upwelling of warm seawater[197]. Although no significant change in polynya occurrence was observed in the Sea of Okhotsk, ice production decreased by 11.4 ± 10.4% over 1988-2008[198]. The decrease was attributed to warm autumn air temperatures, which slowed the advance of the sea-ice cover[198].

In the Antarctic, there has been a significant 0.7 day decade^{-1} increase in polynya occurrence over the full annual cycle over 1979-2023. However, the trends in polynya occurrence show large regional differences (**Fig. 5d**). The most persistent polynyas occur in the eastern longitudes[199], where they have become longer-lasting and larger[200]. In particular, polynyas in the Pacific coastal sector increased in persistence by ~3.2 days decade^{-1} over 1979-2023. In contrast, polynya occurrence has decreased by ~2.2 days decade^{-1} in the Amundsen and Bellingshausen sector, where a decreasing trend in polynya area was previously observed (1979-2022) and attributed to long-term sea-ice loss[200].

Of all Antarctic polynyas, the highest ice production occurs in the Ross Ice Shelf Polynya region[201]. There, polynyas have been less persistent, declining at a rate of ~0.5 days decade^{-1} over 1979-2023. While this result is consistent with the observed reduction in polynya area and ~30% decrease in ice production in

March-October (1992-2005)[201], polynya areas in the Ross sector can exhibit a cyclical, multiyear pattern related to the Amundsen Sea Low and Southern Annular Mode[200]. While not significant, there has been an intermittent reemergence of the Weddell polynya in the 2010s which may be linked to the Southern Annular Mode[202], although the polynya has been considerably smaller in size than it was in the 1970s[203].

The future sea-ice environment

Sea-ice changes are influenced by a variety of dynamic and thermodynamic processes involving different elements, from the ocean to the atmosphere, and operating across different time-scales. The key atmosphere-ice-ocean processes at play 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 loops[37], sea ice is expected to undergo substantial transformations in the coming decades.

This section reviews the state of knowledge on projected Arctic and Antarctic sea-ice changes (**Fig. 6**). A recurring theme in this discussion is that the knowledge of projected change in sea-ice properties and processes is acutely more limited than that of sea-ice coverage. One reason for this limitation is that future changes are estimated using climate models, which cannot account for all sea-ice properties and processes or, in many cases, their time-evolving aspects (such as sea-ice density evolution). This limitation arises from several factors, including model design constraints (for example, most sea-ice models lack parameterizations for landfast ice formation like grounding or anchoring at icebergs), computational constraints, insufficient spatial resolution (accurate representation of polynyas requires detailed modeling of coastal and katabatic winds), and/or inconsistencies in observations which, in turn, affect the interpretation of model results.

Hemispheric sea-ice extent and area remain the two main diagnostics for the future evolution of the Arctic and Antarctic sea-ice states[15,204]. On large spatial and temporal scales, Arctic sea-ice extent is tightly linked to the climatic forcing, be it the global mean surface temperature or the cumulated CO_2 emissions or the atmospheric CO_2 concentrations. Antarctic sea-ice extent and area show less evident relationships to the large-scale radiative and temperature forcing. However, these diagnostics are limited when it comes to better understanding regional changes, 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 drives changes in sea-ice properties and processes.

Future sea-ice age and thickness

As sea-ice loss continues into the 21st century, sea ice is expected to become increasingly thinner and younger (**Fig. 6**). Few studies have focused on projections of sea-ice thickness, and, as of this writing, none have evaluated projected Arctic sea-ice age or either in the Antarctic. While some climate models project that the mean September Arctic sea-ice thickness will be less than 0.5 m by the end of the 21st century[205,206], several CMIP3 and CMIP5 models simulate thick ice in regions where thick ice is not observed[207,208]. 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

For the Arctic, climate models project that the retreat of sea ice will continue year-round and ultimately lead to ice-free conditions[15,209]. A direct consequence of this retreat is that, for a given location of the Arctic Ocean, sea-ice retreat will occur earlier[210], sea-ice freeze-up will occur later[211], and the duration of the open-water season will lengthen[212,213,214] (**Fig. 6**). The projected increase in open water duration is dominated by delayed freeze-up rather than earlier ice melt[211,215,216], although there is large inter-model spread in freeze-up dates, attributable to model differences[210]. As of this writing, there is no equivalent analysis of the future seasonality of Antarctic sea ice due to the relatively larger uncertainties and inter-model spread[204].

Even so, CMIP6 shows modest improvements in simulating monthly Antarctic sea-ice coverage relative to comparisons with observations and CMIP5 simulations[204].

The future of snow on sea ice is dictated by competing processes such as air temperature, which controls the vapor holding capacity of the air through the Clausius-Clapeyron relationship and the eventual phase of precipitation (liquid or solid), poleward atmospheric moisture transport[217], and the presence of sea ice as a platform for snow accumulation. While the interplay between these processes is complex, model projections generally agree that, despite a projected increase in snowfall, Arctic snow depth on sea ice will decrease through the 21st century (**Fig. 6**) due to delayed ice freeze-up[218,219,220,221] though there is large inter-model spread in CMIP6 simulations[222]. Nevertheless, snow is expected to have a increasing influence on the sea-ice mass budget in the future, as thinner sea ice is more thermodynamically sensitive to an overlying snow cover[1]. Future snow loss and the associated increases in under-ice light levels will have repercussions for the Arctic marine ecosystem[223]. In the Antarctic, the future evolution of snow on sea ice has not yet been examined. However, CMIP6 models show snow-ice formation is a major source of uncertainty in the evolution of Antarctic sea-ice mass balance, with inter-model spread being as large as the multi-model mean signal[224].

The future state of other key thermodynamic features such as sea-ice albedo and melt pond coverage have had limited study[225],[226]. Based on 30 ensemble members from the Community Earth System Model (CESM), the June Arctic surface albedo is projected to decrease by 1% decade^{-1} over 1920-2080 (RCP8.5 forcing) as a result of earlier melt, longer snow-free conditions, and enhanced melt ponding[226] (**Fig. 6**). As projected sea-ice loss continues into the 21st century, the effect of more open ocean on solar absorption surpasses that from the changes in the sea-ice surface state[226]. CMIP5 and CMIP6 models also show a projected decrease in Arctic surface albedo, albeit with large inter-model spread due to differences in the treatment of sea-ice properties and processes (for example, implicit vs. explicit melt ponding[225]) and other model differences[226,227,228]. As of this writing, no equivalent study on Antarctic surface albedo projections has been conducted.

Future sea-ice dynamics

As sea ice continues to thin, climate model projections suggest that the positive trend in winter Arctic sea-ice drift will continue to increase throughout the 21st century[229], but summer drift will decrease. While future positive winter trends can be confidently attributed to wind stress and internal stress terms (from thinner ice) that counteract surface tilt force changes, the origins of future negative summer trends are less clear and may be related to smoother sea ice. The negative trend may be linked to the projected increase in sea surface height over the Arctic Ocean[229]. However, the observed positive trend in ice drift from buoys in summer is not captured by climate models[230,231], which calls to attention the caution needed in the interpretation of future summer trends. There is, to our knowledge, no analysis of projected drift changes for the Antarctic. The relationship between projected drift and projected sea-ice roughness is also absent and a topic of future study.

For the outlook of polynyas, there is considerable uncertainty due to model capabilities and localized processes that influence polynya behavior. In the Antarctic, only half of 27 CMIP6 models simulate off-shore polynyas, and the areas of the polynyas are largely underestimated[232]. For coastal Antarctic polynyas, the simulated areas vary by at least a factor of 2.5, with model resolution being attributed to their differences[232]. 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 significant decrease in polynya frequency in the Ross Sea into the late 21st century (SSP3-7.0 forcing)[233]. The westward shift and deepening of the Amundsen Sea Low weakens winds and reduces ice export out of the Ross Sea, while local shoaling of the ocean mixing layer reduces ocean heat flux, all of which facilitates a more stable ice cover and thus rarer occurrence of polynyas in the model simulations[233]. These results underscore the importance of examining local atmosphere-ice-ocean feedbacks, which can shed light on future polynya conditions.

Summary and future perspectives

At the time of this writing, there is a ramp-up of observational activities leading to the 5th International Polar Year (IPY) in 2032-2033, which presents a tremendous opportunity for coordinated, bi-polar observations of the Arctic and Antarctic sea-ice environments. In this regard, now is the key time to consider what the sea-ice research needs are. 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 will advance knowledge and predictive capabilities of sea ice and its role in Earth's changing climate.

In summary, there have been profound changes in the state of the Arctic sea-ice cover in response to anthropogenic climate change. Arctic sea ice is less extensive, younger, thinner, less reflective, and has a thinner snow cover owing to the lengthening sea-ice melt season. Because of thinner sea ice, the Arctic sea-ice cover is more dynamic, drifting at higher velocities than in the 1980s. Collectively, these structural and dynamical changes modify air–sea exchange, ocean stratification, and large-scale atmospheric circulation, exerting strong influences on the global climate system. Notably, there are regional differences in the long-term changes in Arctic sea-ice conditions, as exemplified by polynyas. Some regions have exhibited more frequent polynya openings (like Baffin Bay) while others exhibited less (Gulf of St. Lawrence) over the last four decades. These regional differences point to the need for better 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. Sea-ice extent, age, and thickness show large year-to-year variability and, in some cases (such as with thickness), the uncertainties in the retrievals and resulting differences between retrieval algorithms exceed the magnitude of estimated trends. The timing of melt onset has exhibited no significant change, nor has snow depth in the Weddell Sea. There are regional differences in the long-term changes in surface albedo, which are attributed to changes in sea-ice areal coverage. Additionally, Antarctic sea-ice dynamics, characterized by strong deformation, divergence, and wind-driven redistribution, govern the sea-ice thickness distribution and seasonal persistence, yet remain insufficiently constrained by observations.

Because of the regional variability of Antarctic sea-ice trends and their drivers, attention should focus on key areas to resolve how differences in sea-ice properties and processes respond to and modulate regional differences in atmosphere and ocean forcing. Particular attention should be directed toward the Weddell Sea, which is the primary origin of Antarctic perennial ice and exerts a disproportionate influence on the circumpolar summer sea-ice extent. Variability and trends in this region strongly modulate the Antarctic sea-ice state. Over 2022-2025, the Weddell Sea has experienced pronounced anomalies, including record low sea-ice extent, changes in ice drift and deformation patterns, and shifts in atmosphere-ocean forcing, all of which challenge the previous perception of relative stability in this sector. This region also has an outsized influence on deep-water formation and global overturning circulation. The Ross Sea, on the other hand, has exhibited the largest variability in winter ice extent, and the Amundsen, Bellingshausen, and eastern Ross Seas have intermittently experienced near complete loss of summer sea ice. Improved observational coverage and process-understanding in these often contrasting regions are critical for constraining Antarctic-wide trends and enhancing predictive capability.

The marked loss of global sea ice has wide-ranging socioeconomic consequences, from coastal erosion in Arctic communities to global food security[19]. While CMIP6 models point towards continued loss of sea ice, the large inter-model spread in the rate of loss is indicative of the large uncertainties present in both near- 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. It is not possible to observe all sea-ice properties and processes to the level of detail needed for perfect climate model simulations due to practical constraints. Therefore, we recommend prioritizing observations of sea-ice variables that are expected to change now and in the coming decades and can inform how the climate system is responding to natural variability and anthropogenic climate change. While all sea-ice properties and processes have levels of importance from different perspectives, from the perspective of understanding Earth's climate, sea ice thickness and surface albedo, and the sea-ice characteristics vital to interpreting their spatiotemporal patterns, are of utmost priority.

Sea-ice thickness is a promising metric for evaluating models, as their ability to capture the springtime ice thickness distribution is strongly related to their ability to reasonably predict the sea-ice areal loss in summer[234,235,236]. Furthermore, Earth system models that exhibit a strong relationship between spring sea-ice thickness and summer areal loss show a smaller spread in projected sea-ice loss[237,238]. Thus, there is strong motivation in advancing sea-ice thickness model-observation assessments, as reliable projections of sea-ice thickness are informative for shipping, ecosystem disruption, and other socioeconomic aspects. To enable robust model assessments focused on sea-ice thickness, progress in the following activities is requisite: a comprehensive evaluation and uncertainty quantification of existing sea-ice thickness products; dedicated validation programs to advance knowledge of complex snow and sea-ice conditions to constrain retrieval uncertainties[78,134,239]; investigations of snow's influence 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.

For 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 Earth system models and identifying deficiencies in model physics[228,240]. Moreover, surface albedo may become an equally promising metric as sea ice thickness for improving sea-ice predictions using data assimilation[241]. Unlike the sea ice thickness record, stable satellite records exist of surface albedo for both hemispheres (such as Ref. [242]). Yet, uncertainty quantification of satellite-derived albedos is limited by the disparate, point-scale nature of in situ observations over sea ice. Unknown uncertainties reduce the utility of satellite-based observations for assessment of Earth system models and data assimilation in forecast models, hindering pathways to more reliable predictions. Thus, we recommend the gathering, standardized processing and synthesis of existing in situ observations to enable robust uncertainty quantification of satellite retrievals, whether it be surface albedo or other sea-ice properties with sparse sampling, like snow depth. Of similar value is 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 can also be aided by model sensitivity studies to help determine the level of detail needed in 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 (implicit vs. explicit snow, melt ponds) on albedo feedbacks can guide what types of sampling (temporal, spatial) and field measurements (snow depth, melt pond albedo) are required to improve specific model physics. Moreover, sensitivity studies can help reveal the importance of both positive and negative feedbacks associated with changing sea-ice properties. This information, in turn, can inform the experimental design of observational programs, like those in the upcoming 5th IPY, to maximize scientific return.

Because of the Arctic's and Antarctic's geography, the atmosphere-ice-ocean interactions unique to each environment affect which sea-ice processes dominate. As a result, Arctic sea ice is expected to respond differently to climate change than Antarctic sea ice. Better understanding is needed of the mechanisms that contribute to hemispheric differences in sea-ice properties, how those relationships evolve in response to climate change, and what impacts changing sea-ice properties have in modifying the energy exchange within the polar and global climate systems. New knowledge in these areas can be achieved through joint observational and modeling efforts that inform and are informed by bi-polar observing programs. Bi-polar observing programs with 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 (like ice shelf stability) and other Earth system components (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)[243]. In this regard, it is the act of bringing disciplinary components together at the earliest stage to identify specific interdisciplinary science questions that can be realistically addressed by a field program. The scientific success of such coordination relies on advanced and inclusive planning, standardized observing protocols, and adherence to open science principles before, during, and after data collection. All of these aspects greatly increase the scientific, operational, and community return on investments.

Lastly, it is prudent to consider what sea-ice properties and processes we will have no or limited access to in the future, but, if the measurements were collected within the next 5 years, could greatly benefit research in the coming decades. 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 can have global significance.

References

1. Maykut, G. A. Energy exchange over young sea ice in the central Arctic. *Journal of Geophysical Research: Oceans* **83**, 3646–3658 (1978).
2. Perovich, D. K., Grenfell, T. C., Light, B. & Hobbs, P. V. Seasonal evolution of the albedo of multiyear Arctic sea ice. *Journal of Geophysical Research: Oceans* **107**, SHE 20-1-SHE 20-13 (2002).
3. Perovich, D. K. & Polashenski, C. Albedo evolution of seasonal Arctic sea ice. *Geophysical Research Letters* **39**, (2012).
4. Morales Maqueda, M. A., Willmott, A. J. & Biggs, N. R. T. Polynya Dynamics: a Review of Observations and Modeling. *Reviews of Geophysics* **42**, (2004).
5. Barber, D. G. & Massom, R. A. Chapter 1 The Role of Sea Ice in Arctic and Antarctic Polynyas. in *Elsevier Oceanography Series* (eds Smith, W. O. & Barber, D. G.) vol. 74 1–54 (Elsevier, 2007).
6. Post, E. *et al.* Ecological Consequences of Sea-Ice Decline. *Science* **341**, 519–524 (2013).
7. Moon, T. A., Druckenmiller, M. L. & Thoman, R. L. NOAA Arctic Report Card 2024 : Executive Summary. https://doi.org/10.25923/B7C7-6431 (2024) doi:10.25923/B7C7-6431.
8. Maslanik, J., Stroeve, J., Fowler, C. & Emery, W. Distribution and trends in Arctic sea ice age through spring 2011. *Geophysical Research Letters* **38**, (2011).
9. Tschudi, M. A., Meier, W. N. & Stewart, J. S. An enhancement to sea ice motion and age products at the National Snow and Ice Data Center (NSIDC). *The Cryosphere* **14**, 1519–1536 (2020).
10. Babb, D. G. *et al.* The Stepwise Reduction of Multiyear Sea Ice Area in the Arctic Ocean Since 1980. *Journal of Geophysical Research: Oceans* **128**, e2023JC020157 (2023).
11. Markus, T., Stroeve, J. C. & Miller, J. Recent changes in Arctic sea ice melt onset, freezeup, and melt season length. *Journal of Geophysical Research: Oceans* **114**, (2009).
12. Stroeve, J. C., Markus, T., Boisvert, L., Miller, J. & Barrett, A. Changes in Arctic melt season and implications for sea ice loss. *Geophysical Research Letters* **41**, 1216–1225 (2014).
13. Bliss, A. C. Passive microwave Arctic sea ice melt onset dates from the advanced horizontal range algorithm 1979–2022. *Sci Data* **10**, 857 (2023).
14. Maslowski, W., Kinney, J. C., Higgins, M. & Roberts, A. The Future of Arctic Sea Ice. *Annual Review of Earth and Planetary Sciences* **40**, 625–654 (2012).
15. Notz, D. & Community, S. Arctic Sea Ice in CMIP6. *Geophysical Research Letters* **47**, e2019GL086749 (2020).
16. Kim, Y.-H., Min, S.-K., Gillett, N. P., Notz, D. & Malinina, E. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. *Nat Commun* **14**, 3139 (2023).
17. Heuzé, C. & Jahn, A. The first ice-free day in the Arctic Ocean could occur before 2030. *Nat Commun* **15**, 10101 (2024).
18. Jahn, A., Holland, M. M. & Kay, J. E. Projections of an ice-free Arctic Ocean. *Nat Rev Earth Environ* **5**, 164–176 (2024).
19. Calvin, K. *et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland.* https://www.ipcc.ch/report/ar6/syr/ (2023) doi:10.59327/IPCC/AR6-9789291691647.
20. Purich, A. & Doddridge, E. W. Record low Antarctic sea ice coverage indicates a new sea ice state. *Commun Earth Environ* **4**, 1–9 (2023).
21. Roach, L. A. & Meier, W. N. Sea ice in 2024. *Nat Rev Earth Environ* **6**, 252–254 (2025).
22. Raphael, M. N., Maierhofer, T. J., Fogt, R. L., Hobbs, W. R. & Handcock, M. S. A twenty-first century structural change in Antarctica's sea ice system. *Commun Earth Environ* **6**, 1–9 (2025).

23. Morrison, A. L., Kay, J. E., Frey, W. R., Chepfer, H. & Guzman, R. Cloud Response to Arctic Sea Ice Loss and Implications for Future Feedback in the CESM1 Climate Model. *Journal of Geophysical Research: Atmospheres* **124**, 1003–1020 (2019).
24. Olonscheck, D., Mauritsen, T. & Notz, D. Arctic sea-ice variability is primarily driven by atmospheric temperature fluctuations. *Nat. Geosci.* **12**, 430–434 (2019).
25. Dörr, J., Årthun, M., Eldevik, T. & Madonna, E. Mechanisms of Regional Winter Sea-Ice Variability in a Warming Arctic. *Journal of Climate* **34**, 8635–8653 (2021).
26. Li, X. *et al.* Tropical teleconnection impacts on Antarctic climate changes. *Nat Rev Earth Environ* **2**, 680–698 (2021).
27. Gregory, J. M. *et al.* Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. *Geophysical Research Letters* **29**, 28-1-28–4 (2002).
28. Serreze, M. C. & Barrett, A. P. Characteristics of the Beaufort Sea High. *Journal of Climate* **24**, 159–182 (2011).
29. Kwok, R. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environ. Res. Lett.* **13**, 105005 (2018).
30. Steele, M. & Boyd, T. Retreat of the cold halocline layer in the Arctic Ocean. *Journal of Geophysical Research: Oceans* **103**, 10419–10435 (1998).
31. Stammerjohn, S. & Maksym, T. Gaining (and losing) Antarctic sea ice: variability, trends and mechanisms. in *Sea Ice* 261–289 (John Wiley & Sons, Ltd, 2017). doi:10.1002/9781118778371.ch10.
32. Haumann, F. A., Gruber, N., Münnich, M., Frenger, I. & Kern, S. Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature* **537**, 89–92 (2016).
33. Martinson, D. G. Evolution of the southern ocean winter mixed layer and sea ice: Open ocean deepwater formation and ventilation. *Journal of Geophysical Research: Oceans* **95**, 11641–11654 (1990).
34. Manabe, S. & Stouffer, R. J. Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere. *Journal of Geophysical Research: Oceans* **85**, 5529–5554 (1980).
35. Marshall, J. *et al.* The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **372**, 20130040 (2014).
36. Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A. & Newsom, E. R. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geosci* **9**, 549–554 (2016).
37. Goosse, H. *et al.* Quantifying climate feedbacks in polar regions. *Nat Commun* **9**, 1919 (2018).
38. Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T. Y. & Teng, H. Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geosci* **9**, 590–595 (2016).
39. Meehl, G. A. *et al.* Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nat Commun* **10**, 14 (2019).
40. Nghiem, S. V. *et al.* Rapid reduction of Arctic perennial sea ice. *Geophysical Research Letters* **34**, (2007).
41. Wang, Q. *et al.* Physical Properties of Summer Sea Ice in the Pacific Sector of the Arctic During 2008–2018. *Journal of Geophysical Research: Oceans* **125**, e2020JC016371 (2020).
42. Timco, G. W. & Weeks, W. F. A review of the engineering properties of sea ice. *Cold Regions Science and Technology* **60**, 107–129 (2010).

43. Eicken, H., Lovecraft, A. L. & Druckenmiller, M. L. Sea-Ice System Services: A Framework to Help Identify and Meet Information Needs Relevant for Arctic Observing Networks. *ARCTIC* **62**, 119–136 (2009).
44. Webster, M. *et al.* Snow in the changing sea-ice systems. *Nature Clim Change* **8**, 946–953 (2018).
45. Polashenski, C., Perovich, D. & Courville, Z. The mechanisms of sea ice melt pond formation and evolution. *Journal of Geophysical Research: Oceans* **117**, (2012).
46. Webster, M. A. *et al.* Seasonal evolution of melt ponds on Arctic sea ice. *Journal of Geophysical Research: Oceans* **120**, 5968–5982 (2015).
47. Light, B., Perovich, D. K., Webster, M. A., Polashenski, C. & Dadic, R. Optical properties of melting first-year Arctic sea ice. *Journal of Geophysical Research: Oceans* **120**, 7657–7675 (2015).
48. Organization (WMO), W. M. WMO Sea-Ice Nomenclature. https://library.wmo.int/records/item/41953-wmo-sea-ice-nomenclature.
49. Sumata, H., de Steur, L., Divine, D. V., Granskog, M. A. & Gerland, S. Regime shift in Arctic Ocean sea ice thickness. *Nature* **615**, 443–449 (2023).
50. Screen, J. A., Simmonds, I., Deser, C. & Tomas, R. The Atmospheric Response to Three Decades of Observed Arctic Sea Ice Loss. *Journal of Climate* **26**, 1230–1248 (2013).
51. Lang, A., Yang, S. & Kaas, E. Sea ice thickness and recent Arctic warming. *Geophysical Research Letters* **44**, 409–418 (2017).
52. Labe, Z., Peings, Y. & Magnusdottir, G. Contributions of Ice Thickness to the Atmospheric Response From Projected Arctic Sea Ice Loss. *Geophysical Research Letters* **45**, 5635–5642 (2018).
53. Leu, E., Wiktor, J., Søreide, J. E., Berge, J. & Falk-Petersen, S. Increased irradiance reduces food quality of sea ice algae. *Marine Ecology Progress Series* **411**, 49–60 (2010).
54. Leu, E., Søreide, J. E., Hessen, D. O., Falk-Petersen, S. & Berge, J. Consequences of changing sea-ice cover for primary and secondary producers in the European Arctic shelf seas: Timing, quantity, and quality. *Progress in Oceanography* **90**, 18–32 (2011).
55. Melsheimer, C., Spreen, G., Ye, Y. & Shokr, M. First results of Antarctic sea ice type retrieval from active and passive microwave remote sensing data. *The Cryosphere* **17**, 105–126 (2023).
56. Jacobs, S. S. & Comiso, J. C. Climate Variability in the Amundsen and Bellingshausen Seas. *Journal of Climate* **10**, 697–709 (1997).
57. Comiso, J. C., Kwok, R., Martin, S. & Gordon, A. L. Variability and trends in sea ice extent and ice production in the Ross Sea. *Journal of Geophysical Research: Oceans* **116**, (2011).
58. Parkinson, C. L. A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proceedings of the National Academy of Sciences* **116**, 14414–14423 (2019).
59. Massom, R. A. *et al.* Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: Another factor in ice sheet stability? *Journal of Geophysical Research: Oceans* **115**, (2010).
60. Thorndike, A. S., Rothrock, D. A., Maykut, G. A. & Colony, R. The thickness distribution of sea ice. *Journal of Geophysical Research (1896-1977)* **80**, 4501–4513 (1975).
61. Rothrock, D. A., Yu, Y. & Maykut, G. A. Thinning of the Arctic sea-ice cover. *Geophysical Research Letters* **26**, 3469–3472 (1999).
62. Kwok, R. & Rothrock, D. A. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophysical Research Letters* **36**, (2009).
63. Laxon, S., Peacock, N. & Smith, D. High interannual variability of sea ice thickness in the Arctic region. *Nature* **425**, 947–950 (2003).

64. Kwok, R. & Cunningham, G. F. Variability of Arctic sea ice thickness and volume from CryoSat-2. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **373**, 20140157 (2015).
65. Tilling, R. L., Ridout, A. & Shepherd, A. Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data. *Advances in Space Research* **62**, 1203–1225 (2018).
66. Guerreiro, K., Fleury, S., Zakharova, E., Rémy, F. & Kouraev, A. Potential for estimation of snow depth on Arctic sea ice from CryoSat-2 and SARAL/AltiKa missions. *Remote Sensing of Environment* **186**, 339–349 (2016).
67. Kwok, R., Kacimi, S., Webster, M. a., Kurtz, N. t. & Petty, A. a. Arctic Snow Depth and Sea Ice Thickness From ICESat-2 and CryoSat-2 Freeboards: A First Examination. *Journal of Geophysical Research: Oceans* **125**, e2019JC016008 (2020).
68. Kacimi, S. & Kwok, R. Two Decades of Arctic Sea-Ice Thickness from Satellite Altimeters: Retrieval Approaches and Record of Changes (2003–2023). *Remote Sensing* **16**, 2983 (2024).
69. Stern, H. L. Regime Shift in Arctic Ocean Sea-Ice Extent. *Geophysical Research Letters* **52**, e2024GL114546 (2025).
70. Worby, A. P. *et al.* Thickness distribution of Antarctic sea ice. *Journal of Geophysical Research: Oceans* **113**, (2008).
71. Kern, S. ESA-CCI_Phase2_Standardized_Manual_Visual_Ship-Based_SeaIceObservations_v02. 17458688 Bytes World Data Center for Climate (WDCC) at DKRZ https://doi.org/10.26050/WDCC/ESACCIPSMVSBSIOV2 (2020).
72. Kwok, R. & Kacimi, S. Three years of sea ice freeboard, snow depth, and ice thickness of the Weddell Sea from Operation IceBridge and CryoSat-2. *The Cryosphere* **12**, 2789–2801 (2018).
73. Kacimi, S. & Kwok, R. The Antarctic sea ice cover from ICESat-2 and CryoSat-2: freeboard, snow depth, and ice thickness. *The Cryosphere* **14**, 4453–4474 (2020).
74. Fons, S., Kurtz, N. & Bagnardi, M. A decade-plus of Antarctic sea ice thickness and volume estimates from CryoSat-2 using a physical model and waveform fitting. *The Cryosphere* **17**, 2487–2508 (2023).
75. Bocquet, M., Fleury, S., Rémy, F. & Piras, F. Arctic and Antarctic Sea Ice Thickness and Volume Changes From Observations Between 1994 and 2023. *Journal of Geophysical Research: Oceans* **129**, e2023JC020848 (2024).
76. Maksym, T. & Stammerjohn, S. The rise and fall of Antarctic sea ice: Large-scale variability. 215–260 (2025) doi:10.1002/9781394213764.ch06.
77. Kern, S. & Spreen, G. Uncertainties in Antarctic sea-ice thickness retrieval from ICESat. *Annals of Glaciology* **56**, 107–119 (2015).
78. Giles, K. A., Laxon, S. W. & Worby, A. P. Antarctic sea ice elevation from satellite radar altimetry. *Geophysical Research Letters* **35**, (2008).
79. Liu, X., Corney, S. P., Tilling, R. L. & Heil, P. Brief Communication: Retrieval-Driven Spread in Antarctic Winter Freeboards (CryoSat-2, 2013–2018). *EGUsphere* 1–10 (2026) doi:10.5194/egusphere-2026-662.
80. Taylor, P. C., Hegyi, B. M., Boeke, R. C. & Boisvert, L. N. On the Increasing Importance of Air-Sea Exchanges in a Thawing Arctic: A Review. *Atmosphere* **9**, (2018).
81. Webster, M. A., Liu, Z., Light, B. & Perovich, D. K. A Brighter Arctic Ocean: Trends in Solar Partitioning in the Arctic Sea Ice - Ocean System From 1984 to 2024. *Geophysical Research Letters* **53**, e2025GL120478 (2026).
82. Parkinson, C. L. Spatially mapped reductions in the length of the Arctic sea ice season. *Geophysical Research Letters* **41**, 4316–4322 (2014).
83. Parkinson, C. L. Arctic sea ice coverage from 43 years of satellite passive-microwave observations. *Front. Remote Sens.* **3**, (2022).

84. Parkinson, C. L. Trends in the length of the Southern Ocean sea-ice season, 1979–99. *Annals of Glaciology* **34**, 435–440 (2002).
85. Eayrs, C. *et al.* Understanding the Seasonal Cycle of Antarctic Sea Ice Extent in the Context of Longer-Term Variability. *Reviews of Geophysics* **57**, 1037–1064 (2019).
86. Kapsch, M.-L., Graversen, R. G. & Tjernström, M. Springtime atmospheric energy transport and the control of Arctic summer sea-ice extent. *Nature Clim Change* **3**, 744–748 (2013).
87. Mortin, J. *et al.* Melt onset over Arctic sea ice controlled by atmospheric moisture transport. *Geophysical Research Letters* **43**, 6636–6642 (2016).
88. Liu, Z. & Schweiger, A. Synoptic Conditions, Clouds, and Sea Ice Melt Onset in the Beaufort and Chukchi Seasonal Ice Zone. *Journal of Climate* **30**, 6999–7016 (2017).
89. Livingstone, C. E., Singh, K. P. & Gray, A. L. Seasonal and Regional Variations of Active/Passive Microwave Signatures of Sea Ice. *IEEE Transactions on Geoscience and Remote Sensing* **GE-25**, 159–173 (1987).
90. Perovich, D. K. & Richter-Menge, J. A. Regional variability in sea ice melt in a changing Arctic. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **373**, 20140165 (2015).
91. Lin, L., Lei, R., Hoppmann, M., Perovich, D. K. & He, H. Changes in the annual sea ice freeze–thaw cycle in the Arctic Ocean from 2001 to 2018. *The Cryosphere* **16**, 4779–4796 (2022).
92. Drinkwater, M. R. & Liu, X. Seasonal to interannual variability in Antarctic sea-ice surface melt. *IEEE Transactions on Geoscience and Remote Sensing* **38**, 1827–1842 (2000).
93. Nihashi, S. & Cavalieri, D. J. Observational evidence of a hemispheric-wide ice–ocean albedo feedback effect on Antarctic sea-ice decay. *Journal of Geophysical Research: Oceans* **111**, (2006).
94. Andreas, E. L. & Ackley, S. F. On the Differences in Ablation Seasons of Arctic and Antarctic Sea Ice. *Journal of the Atmospheric Sciences* **39**, 440–447 (1982).
95. Maksym, T., Stammerjohn, S. E., Ackley, S. & Massom, R. Antarctic Sea Ice—: A Polar Opposite? *Oceanography* **25**, 140–151 (2012).
96. Drobot, S. D. & Anderson, M. R. An improved method for determining snowmelt onset dates over Arctic sea ice using scanning multichannel microwave radiometer and Special Sensor Microwave/Imager data. *Journal of Geophysical Research: Atmospheres* **106**, 24033–24049 (2001).
97. Bliss, A. C. & Anderson, M. R. Arctic Sea Ice Melt Onset Timing From Passive Microwave-Based and Surface Air Temperature-Based Methods. *Journal of Geophysical Research: Atmospheres* **123**, 9063–9080 (2018).
98. Meier, W. N. & Stroeve, J. An Updated Assessment of the Changing Arctic Sea Ice Cover. *Oceanography* **35**, 10–19 (2022).
99. Peng, G., Steele, M., Bliss, A. C., Meier, W. N. & Dickinson, S. Temporal Means and Variability of Arctic Sea Ice Melt and Freeze Season Climate Indicators Using a Satellite Climate Data Record. *Remote Sensing* **10**, 1328 (2018).
100. Steele, M. & Dickinson, S. The phenology of Arctic Ocean surface warming. *Journal of Geophysical Research: Oceans* **121**, 6847–6861 (2016).
101. Perovich, D., Light, B. & Dickinson, S. Changing ice and changing light: trends in solar heat input to the upper Arctic ocean from 1988 to 2014. *Annals of Glaciology* **61**, 401–407 (2020).
102. Stammerjohn, S., Massom, R., Rind, D. & Martinson, D. Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Research Letters* **39**, (2012).
103. Willmes, S., Bareiss, J., Haas, C. & Nicolaus, M. The importance of diurnal processes for the Seasonal cycle of Sea-ice microwave brightness temperatures during early Summer in the Weddell Sea, Antarctica. *Annals of Glaciology* **44**, 297–302 (2006).

104. Arndt, S., Willmes, S., Dierking, W. & Nicolaus, M. Timing and regional patterns of snowmelt on Antarctic sea ice from passive microwave satellite observations. *Journal of Geophysical Research: Oceans* **121**, 5916–5930 (2016).
105. Arndt, S. & Haas, C. Spatiotemporal variability and decadal trends of snowmelt processes on Antarctic sea ice observed by satellite scatterometers. *The Cryosphere* **13**, 1943–1958 (2019).
106. Xu, R., Zhao, C., Arndt, S. & Haas, C. Dual-frequency radar observations of snowmelt processes on Antarctic perennial sea ice by CFOSCAT and ASCAT. *The Cryosphere* **18**, 5769–5788 (2024).
107. Nihashi, S. & Ohshima, K. I. Relationship between ice decay and solar heating through open water in the Antarctic sea ice zone. *Journal of Geophysical Research: Oceans* **106**, 16767–16782 (2001).
108. Himmich, K. *et al.* Drivers of Antarctic sea ice advance. *Nat Commun* **14**, 6219 (2023).
109. Warren, S. G. Optical properties of ice and snow. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **377**, 20180161 (2019).
110. Mellor, M. Engineering Properties of Snow. *Journal of Glaciology* **19**, 15–66 (1977).
111. Zhang, T. Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics* **43**, (2005).
112. Ledley, T. S. Snow on sea ice: Competing effects in shaping climate. *Journal of Geophysical Research: Atmospheres* **96**, 17195–17208 (1991).
113. Leu, E. *et al.* Arctic spring awakening – Steering principles behind the phenology of vernal ice algal blooms. *Progress in Oceanography* **139**, 151–170 (2015).
114. Laidre, K. L. *et al.* Quantifying the Sensitivity of Arctic Marine Mammals to Climate-Induced Habitat Change. *Ecological Applications* **18**, S97–S125 (2008).
115. Kovacs, K. M., Lydersen, C., Overland, J. E. & Moore, S. E. Impacts of changing sea-ice conditions on Arctic marine mammals. *Mar Biodiv* **41**, 181–194 (2011).
116. Maykut, G. A. The Surface Heat and Mass Balance. in *The Geophysics of Sea Ice* (ed. Untersteiner, N.) 395–463 (Springer US, Boston, MA, 1986). doi:10.1007/978-1-4899-5352-0_6.
117. Sturm, M., Perovich, D. K. & Holmgren, J. Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea. *Journal of Geophysical Research: Oceans* **107**, SHE 19-1-SHE 19-17 (2002).
118. Massom, R. A. *et al.* Snow on Antarctic sea ice. *Reviews of Geophysics* **39**, 413–445 (2001).
119. Sturm, M. & Massom, R. A. Snow in the sea ice system: friend or foe? in *Sea Ice* 65–109 (John Wiley & Sons, Ltd, 2017). doi:10.1002/9781118778371.ch3.
120. Webster, M. A. *et al.* Interdecadal changes in snow depth on Arctic sea ice. *Journal of Geophysical Research: Oceans* **119**, 5395–5406 (2014).
121. Serreze, M. C. Climatological aspects of cyclone development and decay in the Arctic. *Atmosphere-Ocean* **33**, 1–23 (1995).
122. Zhang, X., Walsh, J. E., Zhang, J., Bhatt, U. S. & Ikeda, M. Climatology and Interannual Variability of Arctic Cyclone Activity: 1948–2002. *Journal of Climate* **17**, 2300–2317 (2004).
123. Simmonds, I., Burke, C. & Keay, K. Arctic Climate Change as Manifest in Cyclone Behavior. *Journal of Climate* **21**, 5777–5796 (2008).
124. Webster, M. A., Parker, C., Boisvert, L. & Kwok, R. The role of cyclone activity in snow accumulation on Arctic sea ice. *Nat Commun* **10**, 5285 (2019).
125. Webster, M. A. *et al.* Summer snow on Arctic sea ice modulated by the Arctic Oscillation. *Nat. Geosci.* **17**, 995–1002 (2024).
126. Boisvert, L. N., Webster, M. A., Parker, C. L. & Forbes, R. M. Rainy Days in the Arctic. *Journal of Climate* **36**, 6855–6878 (2023).

127. Dou, T. *et al.* Trends and spatial variation in rain-on-snow events over the Arctic Ocean during the early melt season. *The Cryosphere* **15**, 883–895 (2021).
128. Warren, S. G. *et al.* Snow Depth on Arctic Sea Ice. *Journal of Climate* **12**, 1814–1829 (1999).
129. Lim, W.-I., Park, H.-S., Petty, A. A. & Seo, K.-H. The Role of Summer Snowstorms on Seasonal Arctic Sea Ice Loss. *Journal of Geophysical Research: Oceans* **127**, e2021JC018066 (2022).
130. Chapman-Dutton, H. R. & Webster, M. A. The Effects of Summer Snowfall on Arctic Sea Ice Radiative Forcing. *Journal of Geophysical Research: Atmospheres* **129**, e2023JD040667 (2024).
131. Eicken, H., Grenfell, T. C., Perovich, D. K., Richter-Menge, J. A. & Frey, K. Hydraulic controls of summer Arctic pack ice albedo. *Journal of Geophysical Research: Oceans* **109**, (2004).
132. Jeffries, M. O., Krouse, H. R., Hurst-Cushing, B. & Maksym, T. Snow-ice accretion and snow-cover depletion on Antarctic first-year sea-ice floes. *Annals of Glaciology* **33**, 51–60 (2001).
133. Maksym, T. & Markus, T. Antarctic sea ice thickness and snow-to-ice conversion from atmospheric reanalysis and passive microwave snow depth. *Journal of Geophysical Research: Oceans* **113**, (2008).
134. Sea ice. in *Polar Remote Sensing: Volume I: Atmosphere and Oceans* (eds Lubin, D. & Massom, R.) 309–728 (Springer, Berlin, Heidelberg, 2006). doi:10.1007/3-540-30785-0_5.
135. Nicolaus, M. *et al.* Snow Depth and Air Temperature Seasonality on Sea Ice Derived From Snow Buoy Measurements. *Front. Mar. Sci.* **8**, (2021).
136. Arndt, S., Maaß, N., Rossmann, L. & Nicolaus, M. From snow accumulation to snow depth distributions by quantifying meteoric ice fractions in the Weddell Sea. *The Cryosphere* **18**, 2001–2015 (2024).
137. Shen, X., Ke, C.-Q. & Li, H. Snow depth product over Antarctic sea ice from 2002 to 2020 using multisource passive microwave radiometers. *Earth System Science Data* **14**, 619–636 (2022).
138. Flanner, M. G., Shell, K. M., Barlage, M., Perovich, D. K. & Tschudi, M. A. Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. *Nature Geosci* **4**, 151–155 (2011).
139. Pistone, K., Eisenman, I. & Ramanathan, V. Radiative Heating of an Ice-Free Arctic Ocean. *Geophysical Research Letters* **46**, 7474–7480 (2019).
140. Riihelä, A., Bright, R. M. & Anttila, K. Recent strengthening of snow and ice albedo feedback driven by Antarctic sea-ice loss. *Nat. Geosci.* **14**, 832–836 (2021).
141. Duspayev, A., Flanner, M. G. & Riihelä, A. Earth's Sea Ice Radiative Effect From 1980 to 2023. *Geophysical Research Letters* **51**, e2024GL109608 (2024).
142. Pistone, K., Eisenman, I. & Ramanathan, V. Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proceedings of the National Academy of Sciences* **111**, 3322–3326 (2014).
143. Riihelä, A., Manninen, T. & Laine, V. Observed changes in the albedo of the Arctic sea-ice zone for the period 1982–2009. *Nature Clim Change* **3**, 895–898 (2013).
144. Light, B. *et al.* Arctic sea ice albedo: Spectral composition, spatial heterogeneity, and temporal evolution observed during the MOSAiC drift. *Elementa: Science of the Anthropocene* **10**, 000103 (2022).
145. Sledd, A. & L'Ecuyer, T. How Much Do Clouds Mask the Impacts of Arctic Sea Ice and Snow Cover Variations? Different Perspectives from Observations and Reanalyses. *Atmosphere* **10**, 12 (2019).
146. Donohoe, A., Blanchard-Wrigglesworth, E., Schweiger, A. & Rasch, P. J. The Effect of Atmospheric Transmissivity on Model and Observational Estimates of the Sea Ice Albedo Feedback. *Journal of Climate* **33**, 5743–5765 (2020).

147. Rantanen, M. *et al.* The Arctic has warmed nearly four times faster than the globe since 1979. *Commun Earth Environ* **3**, 1–10 (2022).
148. Schröder, D., Feltham, D. L., Flocco, D. & Tsamados, M. September Arctic sea-ice minimum predicted by spring melt-pond fraction. *Nature Clim Change* **4**, 353–357 (2014).
149. McCrystall, M. R., Stroeve, J., Serreze, M., Forbes, B. C. & Screen, J. A. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nat Commun* **12**, 6765 (2021).
150. Hutchings, J. K., Roberts, A., Geiger, C. A. & Richter-Menge, J. Spatial and temporal characterization of sea-ice deformation. *Annals of Glaciology* **52**, 360–368 (2011).
151. McPhee, M. G. The sea ice–ocean boundary layer. in *Sea Ice* 138–159 (John Wiley & Sons, Ltd, 2017). doi:10.1002/9781118778371.ch5.
152. Leppäranta, M. *The Drift of Sea Ice*. (Springer, Berlin, Heidelberg, 2011). doi:10.1007/978-3-642-04683-4.
153. Nürnberg, D. *et al.* Sediments in Arctic sea ice: Implications for entrainment, transport and release. *Marine Geology* **119**, 185–214 (1994).
154. Pfirman, S. L., Eicken, H., Bauch, D. & Weeks, W. F. The potential transport of pollutants by Arctic sea ice. *Science of The Total Environment* **159**, 129–146 (1995).
155. Macdonald, R. W., Harner, T. & Fyfe, J. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. *Science of The Total Environment* **342**, 5–86 (2005).
156. Kanhai, L. D. K., Gardfeldt, K., Krumpen, T., Thompson, R. C. & O'Connor, I. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. *Sci Rep* **10**, 5004 (2020).
157. Rigor, I. G. & Wallace, J. M. Variations in the age of Arctic sea-ice and summer sea-ice extent. *Geophysical Research Letters* **31**, (2004).
158. Thorndike, A. S. & Colony, R. Sea ice motion in response to geostrophic winds. *Journal of Geophysical Research: Oceans* **87**, 5845–5852 (1982).
159. Rigor, I. G., Wallace, J. M. & Colony, R. L. Response of Sea Ice to the Arctic Oscillation. *Journal of Climate* **15**, 2648–2663 (2002).
160. Kwok, R., Spreen, G. & Pang, S. Arctic sea ice circulation and drift speed: Decadal trends and ocean currents. *Journal of Geophysical Research: Oceans* **118**, 2408–2425 (2013).
161. Overland, J. E. Atmospheric boundary layer structure and drag coefficients over sea ice. *Journal of Geophysical Research: Oceans* **90**, 9029–9049 (1985).
162. Tsamados, M. *et al.* Impact of Variable Atmospheric and Oceanic Form Drag on Simulations of Arctic Sea Ice. *Journal of Physical Oceanography* **44**, 1329–1353 (2014).
163. Stammerjohn, S. E., Martinson, D. G., Smith, R. C., Yuan, X. & Rind, D. Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. *Journal of Geophysical Research: Oceans* **113**, (2008).
164. Hakkinen, S., Proshutinsky, A. & Ashik, I. Sea ice drift in the Arctic since the 1950s. *Geophysical Research Letters* **35**, (2008).
165. Rampal, P., Weiss, J. & Marsan, D. Positive trend in the mean speed and deformation rate of Arctic sea ice, 1979–2007. *Journal of Geophysical Research: Oceans* **114**, (2009).
166. Spreen, G., Kwok, R. & Menemenlis, D. Trends in Arctic sea ice drift and role of wind forcing: 1992–2009. *Geophysical Research Letters* **38**, (2011).
167. Howell, S. E. L. *et al.* A Comparison of Arctic Ocean Sea Ice Export Between Nares Strait and the Canadian Arctic Archipelago. *Journal of Geophysical Research: Oceans* **128**, e2023JC019687 (2023).

168. Smedsrud, L. H., Halvorsen, M. H., Stroeve, J. C., Zhang, R. & Kloster, K. Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. *The Cryosphere* **11**, 65–79 (2017).
169. Kwok, R., Pang, S. S. & Kacimi, S. Sea ice drift in the Southern Ocean: Regional patterns, variability, and trends. *Elementa: Science of the Anthropocene* **5**, 32 (2017).
170. Maksym, T. Arctic and Antarctic Sea Ice Change: Contrasts, Commonalities, and Causes. *Annual Review of Marine Science* **11**, 187–213 (2019).
171. Holland, P. R. & Kwok, R. Wind-driven trends in Antarctic sea-ice drift. *Nature Geosci* **5**, 872–875 (2012).
172. Radionov, V. F., Bryazgin, N. N. & Alexandrov, E. I. The Snow Cover of the Arctic Basin. *Technical Report*.
173. Landy, J. C., Ehn, J. K. & Barber, D. G. Albedo feedback enhanced by smoother Arctic sea ice. *Geophysical Research Letters* **42**, 10,714-10,720 (2015).
174. Kwok, R., Cunningham, G. F., Zwally, H. J. & Yi, D. ICESat over Arctic sea ice: Interpretation of altimetric and reflectivity profiles. *Journal of Geophysical Research: Oceans* **111**, (2006).
175. Mchedlishvili, A., Lüpkes, C., Petty, A., Tsamados, M. & Spreen, G. New estimates of pan-Arctic sea ice–atmosphere neutral drag coefficients from ICESat-2 elevation data. *The Cryosphere* **17**, 4103–4131 (2023).
176. Krumpen, T. *et al.* Smoother sea ice with fewer pressure ridges in a more dynamic Arctic. *Nat. Clim. Chang.* **15**, 66–72 (2025).
177. Toyota, T. *et al.* The Interannual Variability of Sea Ice Area, Thickness, and Volume in the Southern Sea of Okhotsk and Its Likely Factors. *Journal of Geophysical Research: Oceans* **127**, e2022JC019069 (2022).
178. Toyota, T. Measuring sea ice from space. in *Reference Module in Earth Systems and Environmental Sciences* (Elsevier, 2024). doi:10.1016/B978-0-323-85242-5.00023-3.
179. Tin, T. & Jeffries, M. O. Sea-ice thickness and roughness in the Ross Sea, Antarctica. *Annals of Glaciology* **33**, 187–193 (2001).
180. Weeks, W. F., Ackley, S. F. & Govoni, J. Sea ice ridging in the Ross Sea, Antarctica, as compared with sites in the Arctic. *Journal of Geophysical Research: Oceans* **94**, 4984–4988 (1989).
181. Golledge, N. R. *et al.* Antarctic coastal polynyas in the global climate system. *Nat Rev Earth Environ* **6**, 126–139 (2025).
182. Smith Jr., W. O. & Gordon, L. I. Hyperproductivity of the Ross Sea (Antarctica) polynya during austral spring. *Geophysical Research Letters* **24**, 233–236 (1997).
183. Arrigo, K. R. & van Dijken, G. L. Phytoplankton dynamics within 37 Antarctic coastal polynya systems. *Journal of Geophysical Research: Oceans* **108**, (2003).
184. Tremblay, J.-E. & Smith, W. O. Chapter 8 Primary Production and Nutrient Dynamics in Polynyas. in *Elsevier Oceanography Series* (eds Smith, W. O. & Barber, D. G.) vol. 74 239–269 (Elsevier, 2007).
185. von Berg, L. *et al.* Weddell Sea Phytoplankton Blooms Modulated by Sea Ice Variability and Polynya Formation. *Geophysical Research Letters* **47**, e2020GL087954 (2020).
186. Stirling, I. The Biological Importance of Polynyas in the Canadian Arctic. *Arctic* **33**, 303–315 (1980).
187. Stirling, I. The importance of polynyas, ice edges, and leads to marine mammals and birds. *Journal of Marine Systems* **10**, 9–21 (1997).
188. Nihashi, S. & Ohshima, K. I. Circumpolar Mapping of Antarctic Coastal Polynyas and Landfast Sea Ice: Relationship and Variability. *Journal of Climate* **28**, 3650–3670 (2015).

189. Massom, R. A., Harris, P. T., Michael, K. J. & Potter, M. J. The distribution and formative processes of latent-heat polynyas in East Antarctica. *Annals of Glaciology* **27**, 420–426 (1998).
190. Roberts, A., Allison, I. & Lytle, V. I. Sensible- and latent-heat-flux estimates over the Mertz Glacier polynya, East Antarctica, from in-flight measurements. *Annals of Glaciology* **33**, 377–384 (2001).
191. Martin, S., Drucker, R., Kwok, R. & Holt, B. Estimation of the thin ice thickness and heat flux for the Chukchi Sea Alaskan coast polynya from Special Sensor Microwave/Imager data, 1990–2001. *Journal of Geophysical Research: Oceans* **109**, (2004).
192. Fiedler, E. K., Lachlan-Cope, T. A., Renfrew, I. A. & King, J. C. Convective heat transfer over thin ice covered coastal polynyas. *Journal of Geophysical Research: Oceans* **115**, (2010).
193. Martin, S. & Cavalieri, D. J. Contributions of the Siberian shelf polynyas to the Arctic Ocean intermediate and deep water. *Journal of Geophysical Research: Oceans* **94**, 12725–12738 (1989).
194. Martin, S., Drucker, R. & Yamashita, K. The production of ice and dense shelf water in the Okhotsk Sea polynyas. *Journal of Geophysical Research: Oceans* **103**, 27771–27782 (1998).
195. Ohshima, K. I. *et al.* Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. *Nature Geosci* **6**, 235–240 (2013).
196. Ohshima, K. I., Nihashi, S. & Iwamoto, K. Global view of sea-ice production in polynyas and its linkage to dense/bottom water formation. *Geoscience Letters* **3**, 13 (2016).
197. Galbraith, P. S. Winter water masses in the Gulf of St. Lawrence. *Journal of Geophysical Research: Oceans* **111**, (2006).
198. Kashiwase, H., Ohshima, K. I. & Nihashi, S. Long-term variation in sea ice production and its relation to the intermediate water in the Sea of Okhotsk. *Progress in Oceanography* **126**, 21–32 (2014).
199. Kern, S. Wintertime Antarctic coastal polynya area: 1992–2008. *Geophysical Research Letters* **36**, (2009).
200. Duffy, G. A., Montiel, F., Purich, A. & Fraser, C. I. Emerging long-term trends and interdecadal cycles in Antarctic polynyas. *Proceedings of the National Academy of Sciences* **121**, e2321595121 (2024).
201. Tamura, T., Ohshima, K. I. & Nihashi, S. Mapping of sea ice production for Antarctic coastal polynyas. *Geophysical Research Letters* **35**, (2008).
202. Campbell, E. C. *et al.* Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. *Nature* **570**, 319–325 (2019).
203. Carsey, F. D. Microwave Observation of the Weddell Polynya. *Monthly Weather Review* **108**, 2032–2044 (1980).
204. Roach, L. A. *et al.* Antarctic Sea Ice Area in CMIP6. *Geophysical Research Letters* **47**, e2019GL086729 (2020).
205. Melia, N., Haines, K. & Hawkins, E. Improved Arctic sea ice thickness projections using bias-corrected CMIP5 simulations. *The Cryosphere* **9**, 2237–2251 (2015).
206. Labe, Z., Magnusdottir, G. & Stern, H. Variability of Arctic Sea Ice Thickness Using PIOMAS and the CESM Large Ensemble. *Journal of Climate* **31**, 3233–3247 (2018).
207. Kwok, R. Observational assessment of Arctic Ocean sea ice motion, export, and thickness in CMIP3 climate simulations. *Journal of Geophysical Research: Oceans* **116**, (2011).
208. Koenigk, T., Devasthale, A. & Karlsson, K.-G. Summer Arctic sea ice albedo in CMIP5 models. *Atmospheric Chemistry and Physics* **14**, 1987–1998 (2014).
209. Hezel, P. J., Fichefet, T. & Massonnet, F. Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs. *The Cryosphere* **8**, 1195–1204 (2014).
210. Smith, A., Jahn, A. & Wang, M. Seasonal transition dates can reveal biases in Arctic sea ice simulations. *The Cryosphere* **14**, 2977–2997 (2020).

211. Lebrun, M., Vancoppenolle, M., Madec, G. & Massonnet, F. Arctic sea-ice-free season projected to extend into autumn. *The Cryosphere* **13**, 79–96 (2019).

212. Wang, M. & Overland, J. E. Projected future duration of the sea-ice-free season in the Alaskan Arctic. *Progress in Oceanography* **136**, 50–59 (2015).

213. Barnhart, K. R., Miller, C. R., Overeem, I. & Kay, J. E. Mapping the future expansion of Arctic open water. *Nature Clim Change* **6**, 280–285 (2016).

214. Crawford, A., Stroeve, J., Smith, A. & Jahn, A. Arctic open-water periods are projected to lengthen dramatically by 2100. *Commun Earth Environ* **2**, 1–10 (2021).

215. Wang, M., Yang, Q., Overland, J. E. & Stabeno, P. Sea-ice cover timing in the Pacific Arctic: The present and projections to mid-century by selected CMIP5 models. *Deep Sea Research Part II: Topical Studies in Oceanography* **152**, 22–34 (2018).

216. Keen, A. *et al.* An inter-comparison of the mass budget of the Arctic sea ice in CMIP6 models. *The Cryosphere* **15**, 951–982 (2021).

217. Bintanja, R. *et al.* Strong future increases in Arctic precipitation variability linked to poleward moisture transport. *Science Advances* **6**, eaax6869 (2020).

218. Hezel, P. J., Zhang, X., Bitz, C. M., Kelly, B. P. & Massonnet, F. Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century. *Geophysical Research Letters* **39**, (2012).

219. Blanchard-Wrigglesworth, E., Farrell, S. L., Newman, T. & Bitz, C. M. Snow cover on Arctic sea ice in observations and an Earth System Model. *Geophysical Research Letters* **42**, 10,342-10,348 (2015).

220. Webster, M. A., DuVivier, A. K., Holland, M. M. & Bailey, D. A. Snow on Arctic Sea Ice in a Warming Climate as Simulated in CESM. *Journal of Geophysical Research: Oceans* **126**, e2020JC016308 (2021).

221. Li, H. L., Ke, C. Q., Shen, X. Y., Zhu, Q. H. & Cai, Y. An Ensemble Learning Model Reveals Accelerated Reductions in Snow Depth Over Arctic Sea Ice Under High-Emission Scenarios. *Journal of Geophysical Research: Atmospheres* **129**, e2023JD039910 (2024).

222. Chen, S. *et al.* Assessment of Snow Depth over Arctic Sea Ice in CMIP6 Models Using Satellite Data. *Adv. Atmos. Sci.* **38**, 168–186 (2021).

223. Tedesco, L., Vichi, M. & Scoccimarro, E. Sea-ice algal phenology in a warmer Arctic. *Science Advances* **5**, eaav4830 (2019).

224. Li, S., Huang, G., Li, X., Liu, J. & Fan, G. An Assessment of the Antarctic Sea Ice Mass Budget Simulation in CMIP6 Historical Experiment. *Front. Earth Sci.* **9**, (2021).

225. Roeckner, E., Mauritsen, T., Esch, M. & Brokopf, R. Impact of melt ponds on Arctic sea ice in past and future climates as simulated by MPI-ESM. *Journal of Advances in Modeling Earth Systems* **4**, (2012).

226. Holland, M. M. & Landrum, L. Factors affecting projected Arctic surface shortwave heating and albedo change in coupled climate models. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **373**, 20140162 (2015).

227. Karlsson, J. & Svensson, G. Consequences of poor representation of Arctic sea-ice albedo and cloud-radiation interactions in the CMIP5 model ensemble. *Geophysical Research Letters* **40**, 4374–4379 (2013).

228. Kim, D. & Taylor, P. C. What Factors Explain the Current Arctic Albedo and Its Future Change? *Journal of Geophysical Research: Atmospheres* **131**, e2025JD044070 (2026).

229. Ward, J. L. & Tandon, N. F. Why is summertime Arctic sea ice drift speed projected to decrease? *The Cryosphere* **18**, 995–1012 (2024).

230. Rampal, P., Weiss, J., Dubois, C. & Campin, J.-M. IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline. *Journal of Geophysical Research: Oceans* **116**, (2011).
231. Tandon, N. F., Kushner, P. J., Docquier, D., Wettstein, J. J. & Li, C. Reassessing Sea Ice Drift and Its Relationship to Long-Term Arctic Sea Ice Loss in Coupled Climate Models. *Journal of Geophysical Research: Oceans* **123**, 4338–4359 (2018).
232. Mohrmann, M., Heuzé, C. & Swart, S. Southern Ocean polynyas in CMIP6 models. *The Cryosphere* **15**, 4281–4313 (2021).
233. DuVivier, A. K. *et al.* Projections of winter polynyas and their biophysical impacts in the Ross Sea Antarctica. *Clim Dyn* **62**, 989–1012 (2024).
234. Day, J. J., Hawkins, E. & Tietsche, S. Will Arctic sea ice thickness initialization improve seasonal forecast skill? *Geophysical Research Letters* **41**, 7566–7575 (2014).
235. Holland, M. M., Landrum, L., Bailey, D. & Vavrus, S. Changing Seasonal Predictability of Arctic Summer Sea Ice Area in a Warming Climate. *Journal of Climate* **32**, 4963–4979 (2019).
236. Bushuk, M., Winton, M., Bonan, D. B., Blanchard-Wrigglesworth, E. & Delworth, T. L. A Mechanism for the Arctic Sea Ice Spring Predictability Barrier. *Geophysical Research Letters* **47**, e2020GL088335 (2020).
237. Massonnet, F. *et al.* Constraining projections of summer Arctic sea ice. *The Cryosphere* **6**, 1383–1394 (2012).
238. Zhou, X., Wang, B. & Huang, F. Evaluating sea ice thickness simulation is critical for projecting a summer ice-free Arctic Ocean. *Environ. Res. Lett.* **17**, 114033 (2022).
239. Bunzel, F., Notz, D. & Pedersen, L. T. Retrievals of Arctic Sea-Ice Volume and Its Trend Significantly Affected by Interannual Snow Variability. *Geophysical Research Letters* **45**, 11,751-11,759 (2018).
240. Sledd, A. & L'Ecuyer, T. S. A Cloudier Picture of Ice-Albedo Feedback in CMIP6 Models. *Front. Earth Sci.* **9**, 769844 (2021).
241. Rotondo, J. F., Wieringa, M. M., Bitz, C. M., Clancy, R. P. & Cavallo, S. M. Sea ice albedo bounded data assimilation and its impact on modeling: a regional approach. *The Cryosphere* **20**, 1523–1542 (2026).
242. Riihelä, A., Jääskeläinen, E. & Kallio-Myers, V. Four decades of global surface albedo estimates in the third edition of the CM SAF cLoud, Albedo and surface Radiation (CLARA) climate data record. *Earth System Science Data* **16**, 1007–1028 (2024).
243. Shupe, M. D. & Rex, M. A Year in the Changing Arctic Sea Ice. *Oceanography* **35**, 224–225 (2022).
244. Comiso, J. Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 4. NASA National Snow and Ice Data Center Distributed Active Archive Center https://doi.org/10.5067/X5LG68MH013O (2023).
245. Arctic Climatology Project, E. B. F. F. Environmental Working Group Arctic Meteorology and Climate Atlas. https://doi.org/10.7265/N5MS3QNJ (2000) doi:10.7265/N5MS3QNJ.
246. Holt, B. On-Ice Arctic Sea Ice Thickness Measurements by Auger, Core, and Electromagnetic Induction, from the Late 1800s Onward, Version 2. NSIDC https://doi.org/10.7265/WZ0K-4P60 (2019).
247. Grosfeld, K. Online Sea-Ice Knowledge and Data Platform. (2016).
248. Kacimi, S. & Kwok, R. ICESat-2 and CryoSat-2 L4 Monthly Arctic Snow Depth and Sea Ice Thickness, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center https://doi.org/10.5067/04YYIKXW0GJS (2022).

249. Tschudi, M., Meier, W., Stewart, J., Fowler, C. & Maslanik, J. EASE-Grid Sea Ice Age, Version 4. NASA National Snow and Ice Data Center Distributed Active Archive Center https://doi.org/10.5067/UTAV7490FEPB (2019).

250. Tschudi, M., Meier, W., Stewart, J., Fowler, C. & Maslanik, J. Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, Version 4. NASA National Snow and Ice Data Center Distributed Active Archive Center https://doi.org/10.5067/INAWUWO7QH7B (2019).

251. Meier, W., Fetterer, F., Windnagel, A. & Stewart, S. NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4. NSIDC https://doi.org/10.7265/EFMZ-2T65 (2021).

252. Comiso, J. Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 4. (2023) doi:10.5067/X5LG68MH013O.

Data availability

The data used to compute trends can be downloaded from the following references and websites.

- Bootstrap sea-ice concentrations: Ref. [244]
- Melt onset and freeze-up dates, with data publicly available for download at https://earth.gsfc.nasa.gov/cryo/data/arctic-sea-ice-melt: Ref. 11.
- Snow depth:
    - North Pole drifting ice station data: Ref. [245].
    - Compilation of historical observations of Arctic snow depth: Ref. [246].
    - Cold Regions Research and Engineering Laboratory Ice Mass Balance Buoys: Perovich, D., J. Richter-Menge, and C. Polashenski, Observing and understanding climate change: Monitoring the mass balance, motion, and thickness of Arctic sea ice, http://imb-crrel-dartmouth.org, 2025.
    - Snow buoy data and processing:
        - Data download: Ref. [247] and on PANGAEA: https://www.pangaea.de/?q=snow+buoy&f.method%5B%5D=Snow+buoy.
        - Data processing: Ref. [135].
    - Operation IceBridge, resampled to 25 km: The snow radar data are available at: https://
    - doi.org/10.5067/FAZTWP500V70, processed, and made available courtesy of Dr. Ron Kwok.
    - ICESat-2 and CryoSat-2 25-km gridded retrievals, resampled to in situ measurement locations: Ref. [248]
- Surface albedo: Ref. [242].
- Arctic sea-ice age: Ref. [249].
- Arctic sea-ice motion: Ref. [250].
- Sea-ice concentration from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, for polynya analysis using an 85% concentration threshold and 7-day threshold for January-March Arctic results and an 85% concentration threshold and 36-day threshold for annual Antarctic results: Ref. [251].

Figures

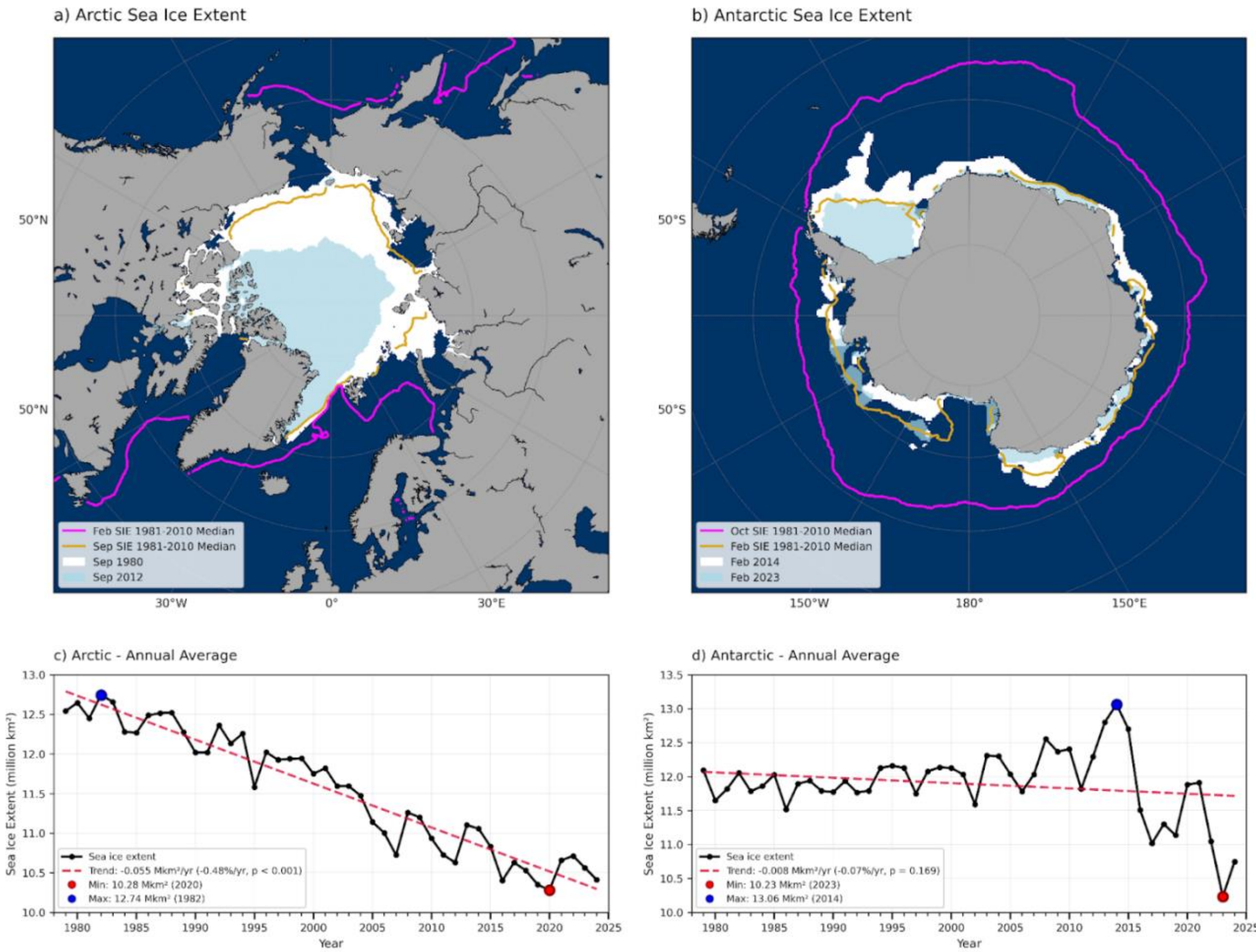

Fig. 1 | Change in sea ice extent over 1979 – 2024. Maps of a) Arctic and b) Antarctic sea ice extent. Contours show the 1981-2010 median sea ice extent for February and October (magenta) and September and February (gold) corresponding to winter maximum and summer minimum extents in the Arctic and Antarctic, respectively. White and light blue shaded areas compare the extent of monthly sea ice extents in late summer (September in the Arctic and February in the Antarctic) during record high and low years (panels c and d). The time-series of annual average sea ice extent are shown for the c) Arctic and d) Antarctic. The Arctic's dominant negative trend (-0.55 million km^2 y^{-1}, $p < 0.001$) contrasts with the pattern of Antarctic sea ice extent change. Sea ice extents were computed from Bootstrap algorithm sea ice concentrations updated from Ref. [244].

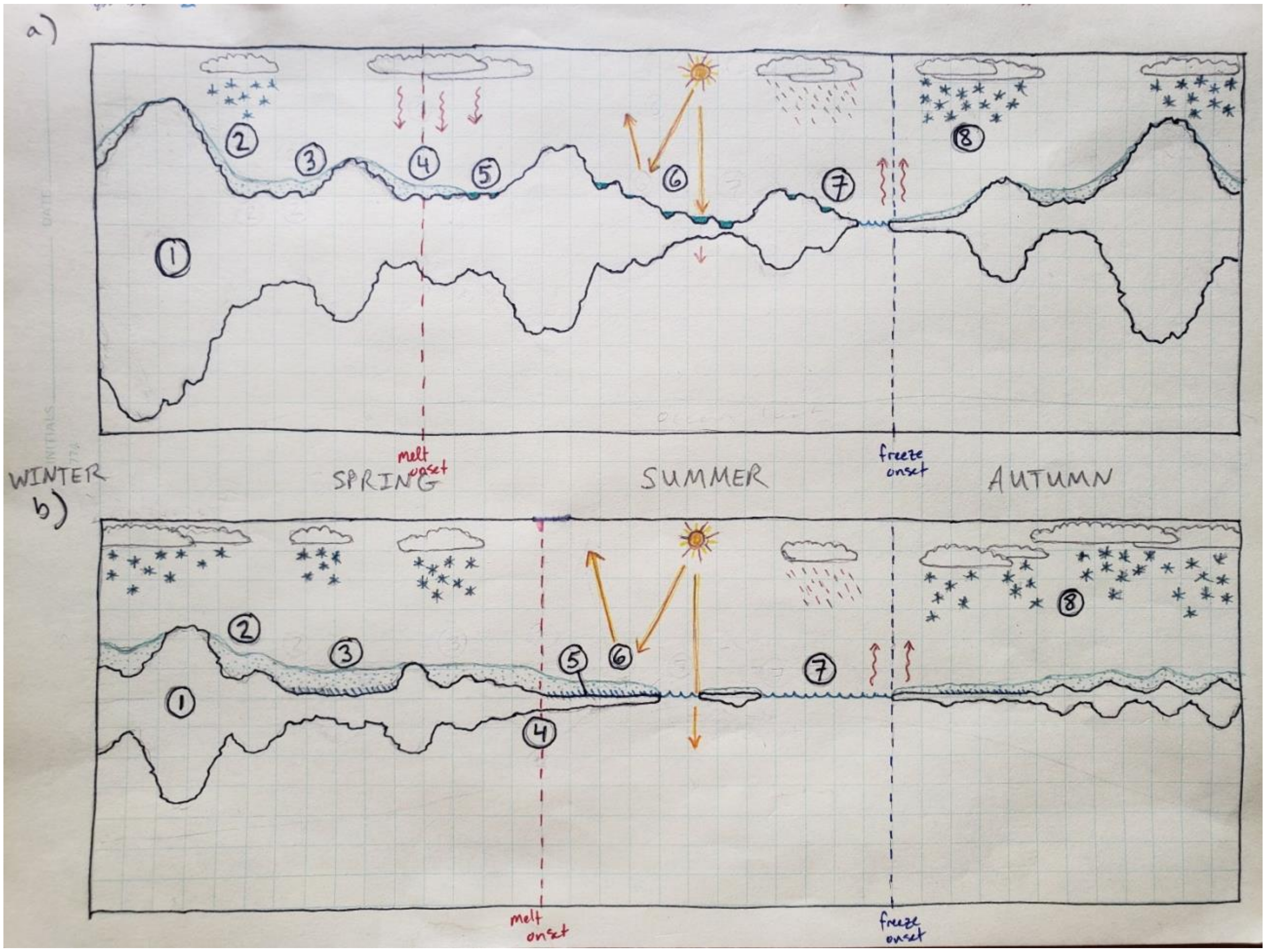

Fig. 2 | Sea-ice properties and processes of the 1980s-2000s in the (a) Arctic and (b) Antarctic environments.

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. Its 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 to the perennial snow cover of Antarctic sea ice.
7. Sea ice in the Arctic tends to persist throughout summer, becoming perennial ice, whereas in the Antarctic, there is a seasonal ice regime, where 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.

Note to peer reviews, the figure will be re-drawn by the Nature team following acceptance.

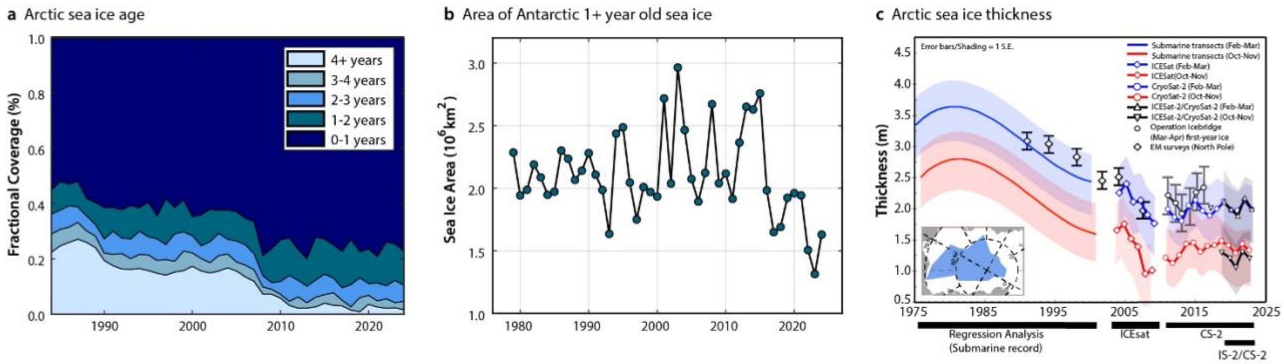

Fig. 3 | Arctic and Antarctic estimates of sea-ice age and mean Arctic sea-ice thickness. a | The fractional coverage of Arctic sea ice of different ages[249] for 1984-2024. **b** | The area of remaining sea ice[244] at the end of the Antarctic melt season[244], representative of Antarctic sea ice that is at least one year old, for 1979-2024. **c** | The Arctic compilation of submarine, surface-based, airborne, and satellite sea-ice thickness measurements for 1975-2023. Figure adapted from figure 6 in ref. 68, with permission from Drs. Sahra Kacimi Ron Kwok. 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.

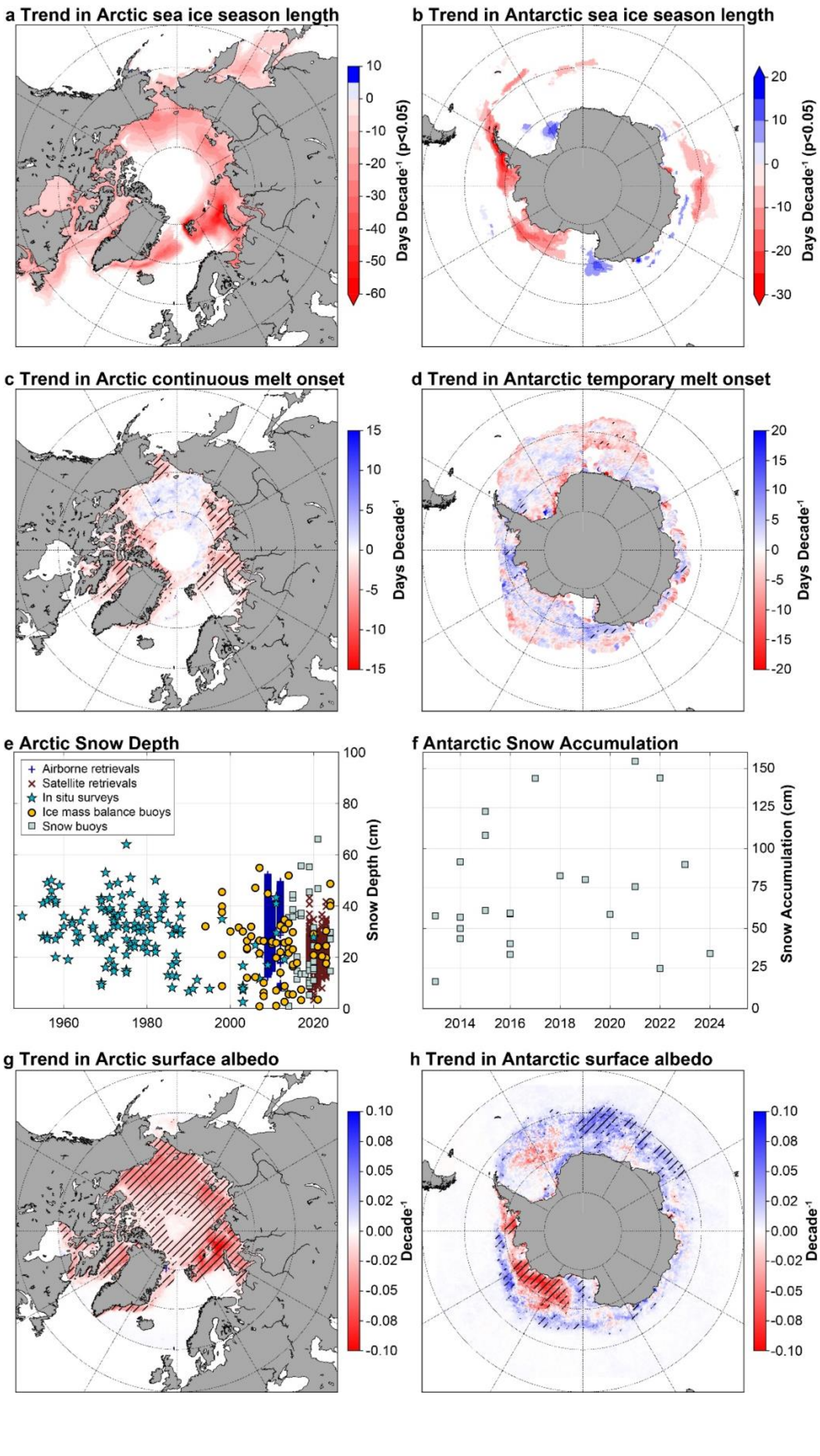
a Trend in Arctic sea ice season length
Days Decade⁻¹ (p<0.05)
10
0
-10
-20
-30
-40
-50
-60
b Trend in Antarctic sea ice season length
Days Decade⁻¹ (p<0.05)
20
10
0
-10
-20
-30
c Trend in Arctic continuous melt onset
Days Decade⁻¹
15
10
5
0
-5
-10
-15
d Trend in Antarctic temporary melt onset
Days Decade⁻¹
20
15
10
5
0
-5
-10
-15
-20
e Arctic Snow Depth
Airborne retrievals
Satellite retrievals
In situ surveys
Ice mass balance buoys
Snow buoys
Snow Depth (cm)
0
20
40
60
80
100
1960
1980
2000
2020
f Antarctic Snow Accumulation
Snow Accumulation (cm)
0
25
50
75
100
125
150
2014
2016
2018
2020
2022
2024
g Trend in Arctic surface albedo
Decade⁻¹
0.10
0.08
0.05
0.02
0.00
-0.02
-0.05
-0.08
-0.10
h Trend in Antarctic surface albedo
Decade⁻¹
0.10
0.08
0.05
0.02
0.00
-0.02
-0.05
-0.08
-0.10

Fig. 4 | Trends in sea-ice thermodynamic characteristics for 1979-2024. The sea-ice season length[244] over 1979-2024 for the **a |** Arctic and **b |** Antarctic. **c |** Trends in the Arctic date of continuous melt onset[11], defined as the day after which sustained surface melting conditions occur. **d |** Trends in the Antarctic date of temporary melt onset[104], defined as the first occurrence of temporary surface snowmelt. The snow depth time-series (see data availability) for the **e |** Arctic from 1954 to 2024 using a combination of airborne and satellite retrievals, in situ surveys, and autonomous drifting buoys, and the **f |** Weddell Sea over 2013-2024 from autonomous drifting buoys. **g |** Trends in clear-sky surface albedo[242] in summer relative to 1979-1998 for the Arctic. **h |** Trends in clear-sky surface albedo[242] in summer relative to 1979-1998 for the Antarctic. In all map panels, hatching indicates regions with statistically significant trends ($p < 0.001$).

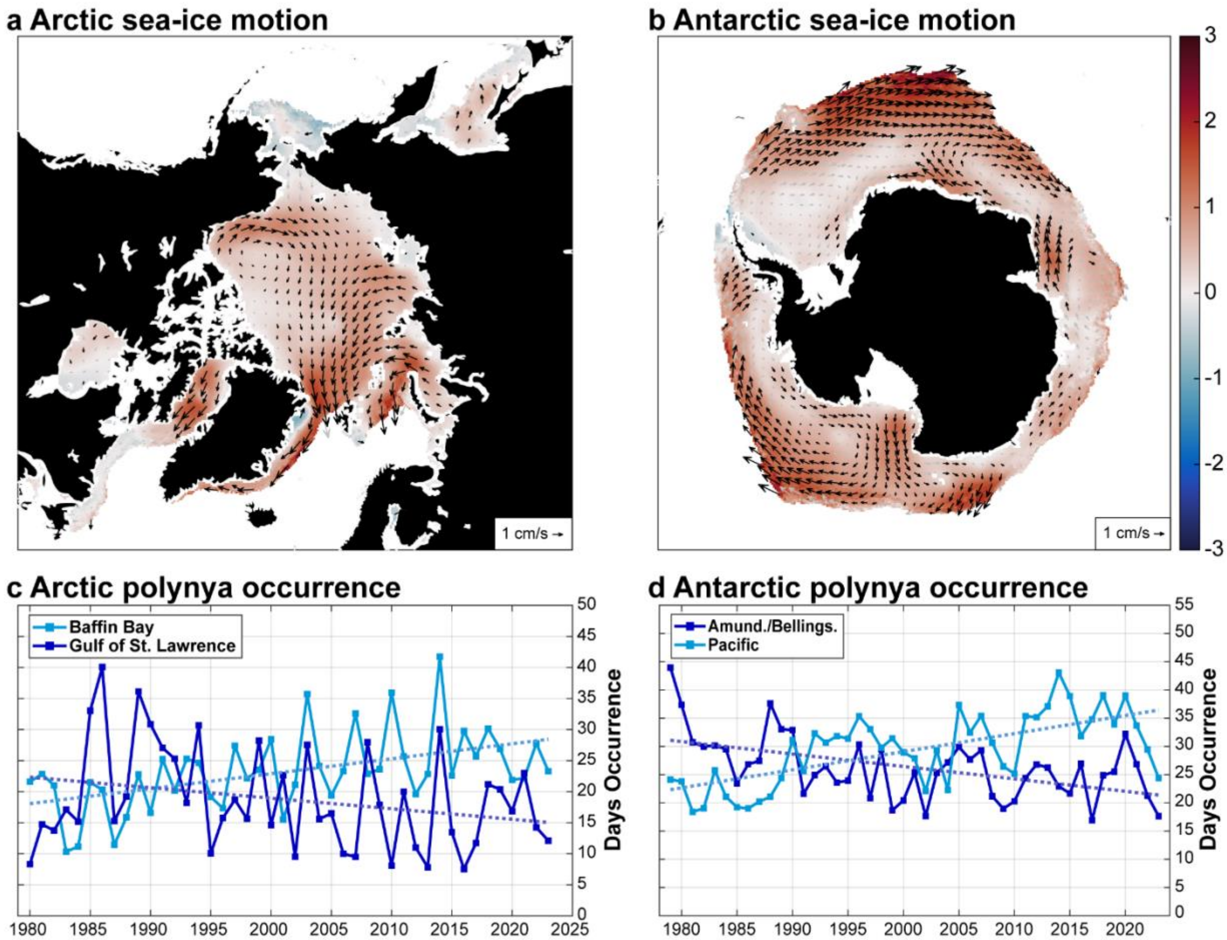

Fig. 5 | Changes in sea-ice motion and polynya occurrence in the Arctic and Antarctic. Trends in the sea-ice motion[250] over **a** | the Arctic (1978-2024), and **b** | the Antarctic (1982-2024). Vector arrows in black signify areas with at least 95% statistical significance, whereas light grey vector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

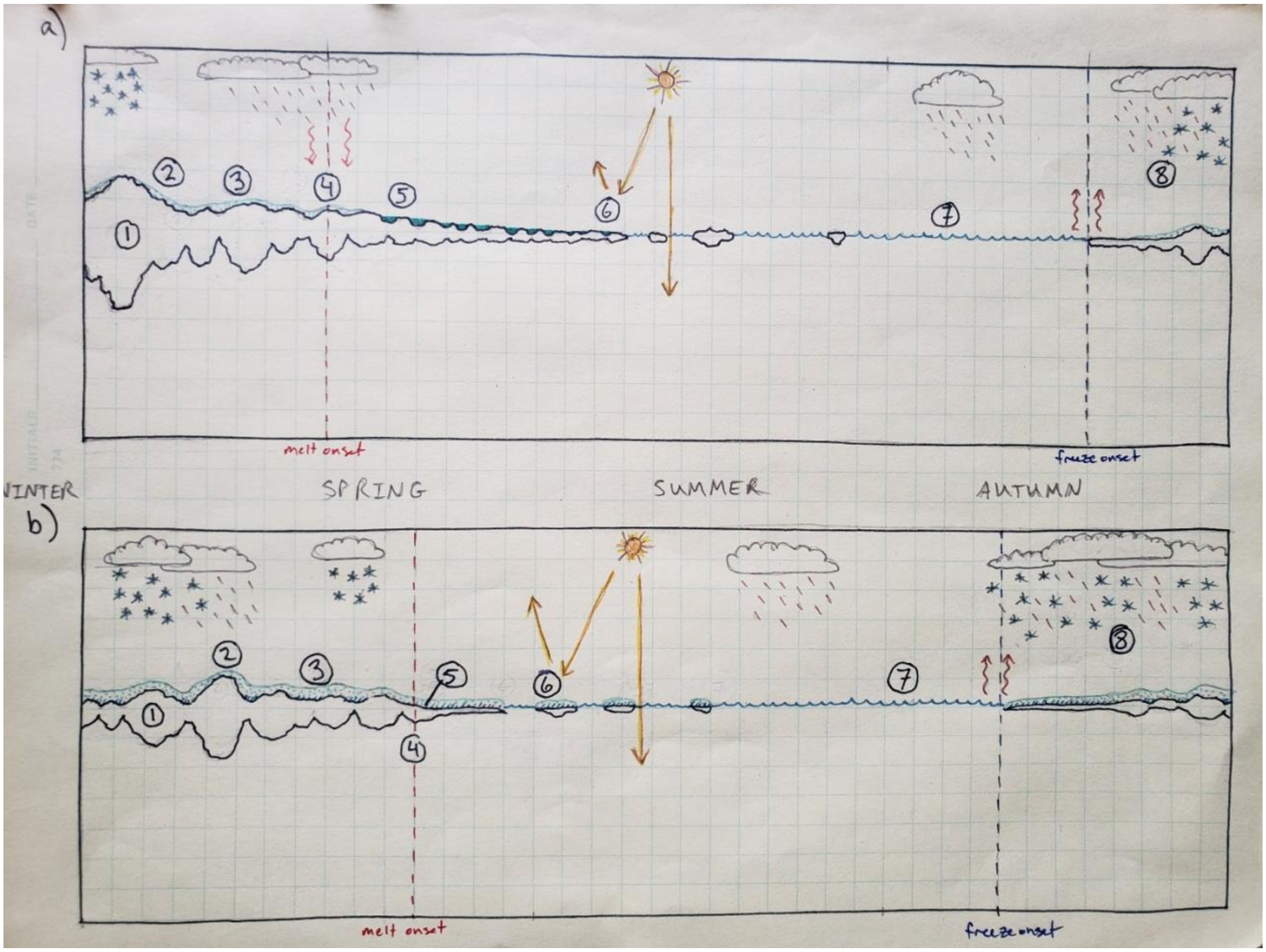

Fig. 6 | Possible future sea-ice properties and processes of the a) Arctic and b) Antarctic environments.

1. Sea ice will 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, creating a more dynamic, less consolidated sea-ice cover.
2. The sea-ice covers in both hemispheres may become smoother over time as 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 will likely thin, owing to later sea-ice formation in the Arctic, which misses the peak snowfall, and, in the Antarctic, possibly more snow-ice formation as a result of a thinner sea-ice cover. Thinner snow may allow sea ice to grow thicker in autumn in a negative feedback. However, thinner snow will also allow more solar radiation to penetrate the sea-ice covers and underlying ocean earlier in spring, which will cause a positive feedback.
4. Melt onset will occur earlier in both hemispheres. In the Arctic, earlier surface melt will hasten sea-ice melt through a positive albedo feedback. In the Antarctic, earlier bottom melt may enhance flooding.
5. More melt ponding may occur in the Arctic as a result of less hummocky ice, which will hasten surface, internal, and bottom ice melt, leading to floe degradation. In the Antarctic, if air temperatures are sufficiently warm, flooding and bottom melt may promote internal melting of the sea-ice cover until floes disintegrate.
6. Both hemispheres will have lower surface albedos, which will increase light levels and solar heating in the upper ocean in summer and cause subsequent ecosystem shifts and disruptions.
7. The duration of open water season will increase in both hemispheres, leading to more wave action, coastal erosion, and solar heating of the ocean. In the Arctic, later sea-ice freeze-up will be the

primary contributor to the lengthening of the open water season. In the Antarctic, it is uncertain how melt and freeze onset timing will change.

8. In both hemispheres, the precipitation cycles will likely shift and contain more ephemeral rainfall events throughout the sea-ice growth season, which will contribute to a more vertically-complex snowpack on Arctic and Antarctic sea ice.

Note to peer reviews, the figure will be re-drawn by the Nature team following acceptance.

Table 1 | **Summary of trends in sea-ice properties and processes reported in this review.**

Variable	Source Data	Domain	Trend	Season	Period	Data Reference
Sea-ice extent	Passive microwave, sea ice concentration satellite retrieval	Arctic	-4.8% decade^{-1}	Annual	1979-2024	Ref. [252]
	Passive microwave, sea ice concentration satellite retrieval	Antarctic	No significant trend	Annual	1979-2024	Ref. [252]
Age (multiyear ice coverage)	Passive microwave, ice type satellite retrieval	Arctic	-0.74% decade^{-1}	Spring	1984-2024	Ref. 9
	Passive microwave, minimum summertime area from ice concentration satellite retrieval	Antarctic	No significant trend	Summer	1979-2024	Ref. [251]
Thickness	Submarine, satellite/airborne radar & laser altimetry, ice thickness retrieval	Arctic, submarine data release area	1.6 m total	Winter	1980-2023	Ref. 68
	n/a	Antarctic	n/a	n/a	n/a	n/a
Sea-ice season	Passive microwave, sea ice concentration satellite retrieval	Arctic	-11.6 days decade^{-1}	n/a	1979-2024	Ref. [252]
	Passive microwave, sea ice concentration satellite retrieval	Antarctic	-1.6 days decade^{-1}	n/a	1979-2024	Ref. [252]
Melt onset	Passive microwave, melt onset satellite retrieval	Arctic (continuous melt onset)	1.8 days decade^{-1}	n/a	1979-2024	Ref. 11
	Passive microwave, melt onset satellite retrieval	Antarctic (temporary melt onset)	No significant trend	n/a	1979-2024	Ref. [104]
Freeze onset	Passive microwave, freeze onset satellite retrieval	Arctic	5.6 days decade^{-1}	n/a	1979-2024	Ref. 11
	n/a	Antarctic	n/a	n/a	n/a	n/a

Melt season length	Passive microwave, melt onset & freeze onset satellite retrieval	Arctic	7.4 days decade^{-1}	n/a	1979-2024	Ref. 11
	n/a	Antarctic	n/a	n/a	n/a	n/a
Snow depth	In situ, autonomous buoy, & airborne/satellite retrievals	Arctic	-2.5 cm decade^{-1}	Spring	1954-2024	See Data Availability Section
	Autonomous buoy	Antarctic (Weddell Sea)	No significant trend	Spring	2013-2024	Refs. 135, 136
Albedo	Passive reflectance imaging, satellite retrieval	Arctic	-0.030 decade^{-1}	Summer	1979-2020	Ref. 242
	Passive reflectance imaging, satellite retrieval	Antarctic	0.002 decade^{-1}	Summer	1979-2020	Ref. 242
Motion (drift)	Passive microwave, satellite retrieval	Arctic	0.63 cm s^{-1} decade^{-1}	Spring	1978-2024	Ref. 9
	Passive microwave, satellite retrieval	Antarctic	0.69 cm s^{-1} decade^{-1}	Spring	1982-2024	Ref. 9
Polynya occurrence	Passive microwave, sea-ice concentration satellite retrieval	Arctic (north of 59°N)	2.4 days decade^{-1}	Winter	1979-2023	Ref. 251
	Passive microwave, sea-ice concentration satellite retrieval	Arctic (south of 59°N)	-1.6 days decade^{-1}	Winter	1979-2023	Ref. 251
	Passive microwave, sea-ice concentration satellite retrieval	Antarctic (Pacific sector)	3.2 days decade^{-1}	Annual	1979-2023	Ref. 251
	Passive microwave, sea-ice concentration satellite retrieval	Antarctic (Amundsen/Bellingshausen sector)	-2.2 days decade^{-1}	Annual	1979-2023	Ref. 251

Acknowledgements

M.A.W. conducted this work under the National Science Foundation projects 2325430 and 2333380, Office of Naval Research project N00014-23-1-2484, and NASA's ICESat-2 project NNH22ZDA001N-ICESAT2-0021. S.A. was supported by the Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, the University of Hamburg, the German Research Foundation's (DFG) projects fAntasie (AR1236/3-1) and SnowCast (AR1236/1-1) within its priority program "Antarctic Research with comparative investigations in the Arctic ice areas" (SPP1158), and the DFG Emmy Noether Programme project SNOWflAke (493362232). The work of A.R. was financially supported by the Research Council of Finland, decision #364711.

Competing interests

The authors declare no competing interests in relation to the work described.

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 figures and writing and editing the manuscript.