

Section 4

Subchapter 5K

High-latitude ice

Writing team: Walker O. Smith, Jr. (coordinating author), Ted Maksym, Enrique Marschoff (lead member), Robert A. Massom, Olga V. Sergienko, Vasily Smolyanitsky (co-lead member) and Sharon E. Stammerjohn.

Key points

- Loss of continental ice has accelerated from the Greenland ice sheet since the early 1990s and from Antarctic ice sheets since the late 1990s, contributing 21.0 mm to global sea-level rise from 1992 to 2020.
- Arctic sea ice will continue to decline in the future, leading to model predictions of occurrences of an ice-free Arctic Ocean during Septembers by mid-21st century.
- The abrupt reduction in Antarctic sea ice extent and duration since 2016 may herald a fundamental change in the Southern Ocean.

1. Introduction

The present subchapter focuses on two key components of Earth's climate system - sea ice and ice sheets - and how they respond to climate change. It highlights the substantial changes occurring in high-latitude cryospheres of both polar regions and their influences on the ocean and atmosphere, in particular physical impacts, as biological impacts were treated previously (United Nations, 2022 a, 2022b). Sea ice forms from freezing seawater as the ocean cools each autumn and winter. Ice sheets, on the other hand, comprise glacial ice formed from snow accumulation over thousands of years which compacts and flows seaward under gravity. The mass loss from ice sheets injects large volumes of freshwater into the ocean and contributes to sea level rise. Sea ice and ice sheets profoundly influence - and are strongly impacted by - the ocean and the atmosphere.

Interactions of the polar cryosphere with the ocean and atmosphere impact global circulation and lower-latitude atmospheric patterns and influence global weather and climate, the ocean's freshwater budget, the uptake of anthropogenic heat and carbon and global sea level rise. Similarly, polar systems are influenced by atmospheric teleconnections to lower-latitudes and ocean variability there. At the same time, changes in the extent, mass, formation and melt, thickness and properties of polar ice can accelerate change via complex feedback processes (Goosse and others, 2018). As a thin veneer that lies between the ocean and atmosphere, sea ice reacts to change and variability in weather patterns and climate drivers at sub-daily, seasonal and decadal time scales. In contrast, the Antarctic and Greenland Ice Sheets respond over centuries to millennia, although more rapid changes are beginning to occur. In short, ice sheets and sea ice are both sensitive indicators and influencers of climate change and variability via highly coupled ocean-atmosphere-cryosphere processes.

2. Arctic and Antarctic sea-ice systems

Similarities and contrasts

Sea ice includes pack ice that is in constant motion due to winds and ocean currents and fast ice that is attached to coastal margins. Each year, Earth's high-latitude oceans are transformed by the advance and retreat of sea ice driven by seasonal changes in ocean and atmosphere temperatures, wind patterns and solar insolation. In the Arctic, sea-ice extent varies between approximately $15 \times 10^6 \text{ km}^2$ in March to approximately $6 \times 10^6 \text{ km}^2$ in September (figure I). The lowest Arctic sea-ice extent since the start of the satellite record in 1979 occurred in September 2012 ($3.39 \times 10^6 \text{ km}^2$). In contrast, Antarctic sea-ice extent varies between approximately $19 \times 10^6 \text{ km}^2$ in September to approximately $3 \times 10^6 \text{ km}^2$ in February (figure II), with the lowest summer minimum on record being in 2023 ($1.79 \times 10^6 \text{ km}^2$). Sea ice greatly influences biological processes in both polar systems by impacting light, nutrients and food availability and by forming habitats for the diverse biota (United Nations, 2017, 2022a).

There are distinct differences between the two polar sea-ice systems due to differences in their geographical settings, processes of sea-ice formation and decay and ice-ocean-atmosphere interactions (Turner and Overland, 2009; Maksym, 2019). Arctic sea ice largely forms within the Arctic Ocean basin and is constrained by adjacent land masses (although sea ice in the Bering and East Greenland Seas is unconstrained). Large-scale sea-ice motion is dominated by an atmospheric high-pressure system in the Western Arctic, the oceanic Transpolar Drift Stream in the central Arctic and the Beaufort Gyre, the first two of which export sea ice into the North Atlantic through the Fram Strait.

In contrast, Antarctic sea ice seasonally expands outward from (then retreats back to) the Antarctic continent, thereby buffering (then exposing) the coastal margins of the Antarctic Ice Sheet (Reid and Massom, 2022). In winter, Antarctic sea ice extends to lower latitudes compared to the Arctic, while continually being exposed to the high winds and waves of the Southern Ocean (Massom and Stammerjohn, 2010). The overall configuration and motion of the Antarctic sea ice reflects large-scale patterns of atmospheric and ocean circulation (Holland and Kwok, 2012). Regional variations in these factors combine to create variations in timings of annual ice-edge advance, retreat, annual duration and maximum and minimum sea-ice extent (Stammerjohn and others, 2008). Antarctic sea-ice extent displays high variability over temporal scales of days to weeks due to changing winds and temperatures associated with the passage of cyclones (Uotila and others, 2011). On seasonal and interannual timescales, sea-ice extent and the timings of sea-ice advance and retreat are influenced by modes of climate variability such as the El Niño-Southern Oscillation (Stammerjohn and others, 2008) and the Southern Annular Mode, the latter being a function of the surface pressure gradient between Antarctica and mid-latitudes (Marshall, 2003).

Sea-ice thickness strongly influences the heat and freshwater budgets of both polar oceans (Maksym and others, 2012). Historically, Arctic sea ice was substantially thicker, with maximum thickness reaching 6 m. In recent years much of the multiyear ice has disappeared and Arctic sea ice is now 1-2 m thick (Kwok, 2018) and largely first-year ice, thus being similar to the typical approximately 1 m thick Antarctic first-year ice (Worby and others, 1998). Fast ice is confined to narrow coastal bands ranging from a few kilometers to hundreds of kilometers wide in both the Antarctic and Arctic – depending on coastal configuration and bathymetry and the distribution of grounded icebergs – and can be annual or perennial (Mahoney, 2018; Fraser and others, 2021).

There are also differences in the oceanic settings of the two polar systems. Arctic water columns are strongly stratified, with low-salinity water at the surface underlain by a cold, salty halocline that insulates the sea ice from the warm, deeper Atlantic Water (Steele and Boyd, 1998). In the Antarctic, the upper water column is substantially saltier (although freshening in recent years)(United Nations, 2022a), allowing mixing to greater depths and a strong upward transfer of heat from warm circumpolar deep water that limits the thermodynamic growth of Antarctic sea ice to approximately 70 cm (Martinson, 1990). Only during summer does the surface of the Southern Ocean become seasonally stratified by sea-ice melt (Haumann and others, 2016).

Due to its high reflectance and low thermal conductivity, snow that accumulates on sea ice substantially modifies the physical and optical properties and growth/melt rates of the ice and its interactions with the ocean and atmosphere (Sturm and Massom, 2017). Snow depths on sea ice tend to be greater in the Antarctic than in the Arctic due to higher precipitation over the Southern Ocean (Webster and others, 2018). Sea ice also seasonally limits solar heating of the upper ocean and also acts as an insulating barrier between the ocean and atmosphere that reduces exchanges of heat and gases (e.g. water vapor, carbon dioxide (CO₂)), as well as vertical mixing of the upper ocean. Seasonal sea-ice formation and decay releases vast volumes of brine and freshwater in winter and/or summer, respectively (Meredith and Brandon, 2017). In coastal regions in the Weddell Sea, Ross Sea, parts of East Antarctica and in the Labrador and Greenland Seas, particularly high rates of sea-ice formation generate large volumes of dense brine, which sink to form bottom waters that drive the global thermohaline circulation (Abernathey and others, 2016).

Greenland and Antarctic ice sheets

Continent-wide estimates of ice-sheet mass budgets for both Greenland and Antarctica have been completed (Otosaka and others, 2023). The Greenland and Antarctic ice sheets together store approximately 68% of Earth's freshwater. The Greenland ice sheet is approximately 1.7×10^6 km² in area, has a mean thickness of 1.67 km and contains 2.9×10^6 km³ of ice (equivalent to a 7.4 m rise in sea level if completely melted; Kulp and Strauss, 2019). It lies on bedrock above sea level and drains into fjords through outlet glaciers. The Antarctic ice sheet covers approximately 14×10^6 km², has a mean thickness of 2.16 km and contains 26.9×10^6 km³ of ice (Fretwell and others, 2013), enough to raise sea level by 58 m if melted. The Antarctic ice sheet has three components: the West and East Antarctic ice sheets and the Antarctic Peninsula. Unlike the Greenland ice sheet and much of the East Antarctic ice sheet, a large portion of the West Antarctic ice sheet rests on bedrock that is below sea level and more vulnerable to climate change than ice-sheet areas that are grounded above sea level. The East Antarctic ice sheet is substantially higher and thicker than the West Antarctic ice sheet (Morlighem and others, 2017) and its response to climate warming represents the largest unknown in projections of future sea-level rise (IPCC, 2023).

Ice sheets affect the ocean by releasing large volumes of freshwater through four processes (Straneo and others, 2019):

- Surface meltwater runoff (extensive across Greenland and the Antarctic Peninsula in summer)
- Discharge of sub-glacial meltwater (largely occurs in Greenland; see figure III)

- Basal melting of floating ice shelves through their contact with warm waters (predominantly for Antarctic ice shelves; see figure IV)
- Iceberg calving.

Icebergs

Calving, the process by which ice mechanically fractures to form icebergs, is a natural and continuous process in the evolution of ice shelves and marine-terminating glaciers and has been estimated to account for half of the ice lost annually from both the Antarctic ice sheet (Depoorter and others, 2013) and the Greenland ice sheet (Shiggins and others, 2023). Icebergs drift large distances, or ground on shallow banks where they reside for multiple years and influence coastal sea-ice processes (polynya and fast-ice formation) and in particular conditions around Antarctica (Barber and Massom, 2007). The Antarctic ice sheet, with its seaward margin of numerous floating ice shelves and ice tongues, produces vast numbers of icebergs that vary greatly in size, with the largest tabular iceberg being over 10,000 km² (Budge and Long, 2018). Greenland icebergs are typically small, with dimensions similar to the thickness of the source glacier front (Reeh and others, 2001).

3. Change and variability in the Arctic Ocean cryosphere system

Arctic sea ice

The response of Arctic sea ice to climate change has been dramatic (all sea ice data are available from the National Snow and Ice Data Center Sea Ice Index and the European Space Agency Climate Change Initiative; see figure V). The current high rate of Arctic sea-ice loss and associated surface-ocean warming is unprecedented in the past 1,500 years (Osborne and others, 2017). Annual sea-ice extent has declined since 1979 (the start of the satellite record) but slowed since 2007, with losses being greatest in the East Siberian, Chukchi, Laptev, Barents and Kara Seas (Jahn and others, 2024). The September reduction in sea-ice extent is greatest in the Beaufort and Chukchi Seas, but the greatest March reduction has been in the Greenland and Barents Seas. The Arctic sea-ice extent summer reduction has increased open-water duration and reduced sea-ice age (Kwok, 2018) and thickness (Petty and others, 2023). Prior to 1970, multiyear ice covered most of the Arctic Ocean (i.e. approximately 5.5 x 10⁶ km² in winter). Thereafter, the multiyear ice area decreased to a minimum of 1.6 x 10⁶ km² in 2017 (Kwok, 2018) and now the Arctic is largely covered by thinner first-year ice that is more vulnerable to seasonal melt (Stroeve and Notz, 2018). Climate models project a continued decline, resulting in an ice-free¹ end of summer Arctic Ocean by 2050 (Kim and others, 2023; Jahn and others, 2024).

Greenland ice sheet

The mass loss of the Greenland ice sheet is the second largest contributor to sea-level rise after ocean thermal expansion (Zemp and others, 2019), contributing approximately 14±2 mm between 1992 and 2020 at a loss rate of 169 gigatons per year, representing a 645% increase relative to its historical contribution (from 1992 to 1996) (Otosaka and others, 2023). The enhanced loss of ice from the

¹ The term “ice-free” used here should not be confused with a formal navigational term “ice-free” of the relevant United Nations bodies (World Meteorological Organization, International Maritime Organization). As icebergs will continue to be present within the domains of the Arctic and Southern Oceans, the term “ice-free” navigationally is not applicable.

Greenland ice sheet results from changes in atmospheric and oceanic forcing that drive increases in surface and submarine melting and calving (Hanna and others, 2024).

4. Change and variability in the Antarctic Ocean-Cryosphere System

Southern Ocean sea ice

The circumpolar average of Antarctic sea-ice extent increased slightly between 1979 and 2015, reaching consecutive record-high winter sea-ice extents in 2012, 2013 and 2014, but then decreased substantially in 2016, reaching consecutive record-low summer sea-ice extents in 2017, 2022, 2023 and 2024. Extreme record-low winter sea-ice extent occurred in 2023 and 2024. Since the winter of 2015, seasonal sea-ice extent has remained largely below the mean from 1979 to 2024 (figure VI), potentially heralding a regime shift in the Southern Ocean (Hobbs and others, 2024). An observed shift to longer persistence of sea-ice anomalies, changed response to atmospheric forcing and increases in the spatial coherence of anomalies (Hobbs and others, 2024; Schroeter and others, 2023) could indicate a fundamental change in the highly coupled sea ice-ocean-atmosphere system (Eayrs and others, 2021; Raphael and Handcock 2022; Purich and Doddridge, 2023).

Antarctic ice sheet

Between 1992 and 2020, the Antarctic ice sheet lost 2,671 gigatons of ice, equivalent to 7.4 mm of sea-level rise or nearly half of the Greenland ice sheet contribution. Antarctica's contribution to sea-level rise increased from 0.14 mm per year between 1992 and 1999 to 0.39 mm per year from 2010 to 2020 (Otosaka and others, 2023). Most of this loss has come from the West Antarctic ice sheet, where major outlet glaciers (Pine Island and Thwaites) have undergone enhanced melting, thinning and retreat leading to increased discharge of grounded ice (Jenkins and others, 2018). The Antarctic Peninsula has shed 13 gigatons per year, while East Antarctica remains near equilibrium. East Antarctica, however, constitutes the most uncertain component in future predictions of Antarctica's contribution to sea level rise (Fricker and others, 2025).

Antarctic ice shelves

Of paramount importance to the Antarctic ice sheet-ocean system is the structural integrity of ice shelves, which are far less common around the Greenland ice sheet (Bindshadler and others, 2011). Ice shelves play a crucial role in moderating the ice sheet's contribution to sea-level rise by buttressing the discharge of grounded ice mass into the ocean, yet they are the most vulnerable part of the ice sheet system, with recent extensive thinning due to basal melting by the increased presence of warm ocean waters within ice shelf cavities (Verfaillie and others, 2022). Moreover, abrupt ice-shelf mechanical disintegration has occurred, caused by thinning, melting and increased exposure to wave forcing along ice shelf fronts (e.g. on the Antarctic Peninsula) (Massom and others, 2018; figure VII). Rates of basal melting and calving vary regionally (Hanna and others, 2024) and are impacted by atmospheric and oceanic forcing. Iceberg calving is the largest factor affecting ice shelf area, whereas ice-front retreat and thinning are secondary factors (Greene and others, 2022). Large calving events (e.g. tabular iceberg B15) can disrupt Antarctic Bottom Water formation by decreasing sea-ice production in coastal polynyas (areas of vigorous ice production driven by persistent off-ice winds; Tamura and others, 2012). In addition, glacial meltwater inputs and ocean freshening can affect sea-ice production and in certain areas (e.g. the Ross Sea) can also influence Antarctic Bottom Water production (Jacobs and Giulivi, 2010). There is substantial concern that

various ice shelf and glacial response processes could lead to rapid ice loss (characterized by the IPCC (2023) as a low-likelihood, high-impact scenario for high rates of sea level rise), but the mechanisms for such collapse are uncertain (e.g. Sergienko, 2022; Morlighem and others, 2024).

5. Outlook

Under the current emission rates of greenhouse gases, ice coverage and volume will continue to decrease and the impacts of this reduction will increase markedly (Chown and others, 2022). With increased open water in both polar regions and the loss of a protective sea-ice buffer, erosion of coastal margins will accelerate due to predicted increased storms and wave heights. Increased ice discharge from ice sheets will result in a heightened sea level, endangering coastal communities globally. Increased shipping and other human activities (e.g. tourism) in both regions will produce disturbance and release of pollutants, endangering regional biota. Loss of sea ice in both regions also has the potential to accentuate climate warming via complex feedback mechanisms (Goosse and others, 2018) which further accelerate ice loss.

6. Key remaining knowledge and capacity gaps

While significant advances have been made to understand processes driving cryospheric change in polar regions, further progress is urgently needed, given the global impacts of ice loss and the fact that climate models cannot as yet reliably predict future changes and their impacts. Specific gaps include:

- Understanding the recent abrupt declines in Antarctic sea ice (in particular those in autumn-winter) and potential future changes
- Quantifying the thickness distributions of Antarctic sea ice and its snow cover and determining whether these are changing
- Understanding subglacial processes under polar ice sheets that control ice discharge into surrounding oceans
- Understanding processes such as supraglacial and subglacial hydrology and iceberg calving mechanisms
- Quantifying processes impacting sea-level rise
- Reducing uncertainty in the timing of an open-water Arctic.

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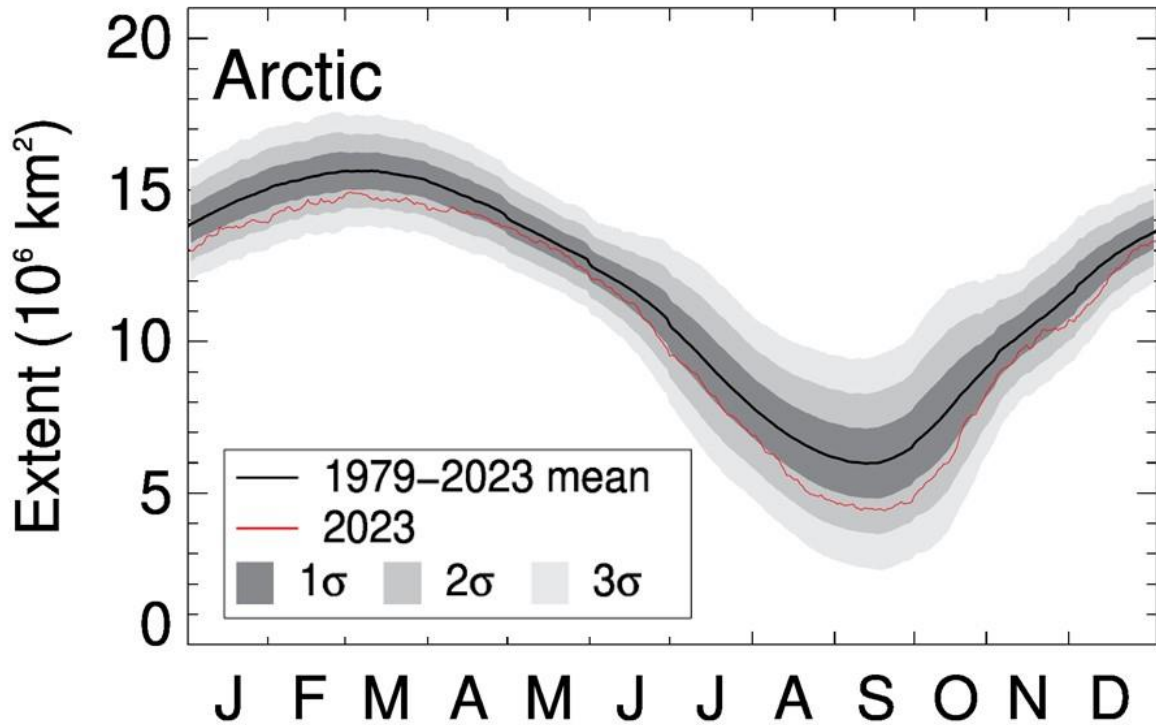
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Figure I

Seasonal mean sea-ice extent in the Arctic and its variability

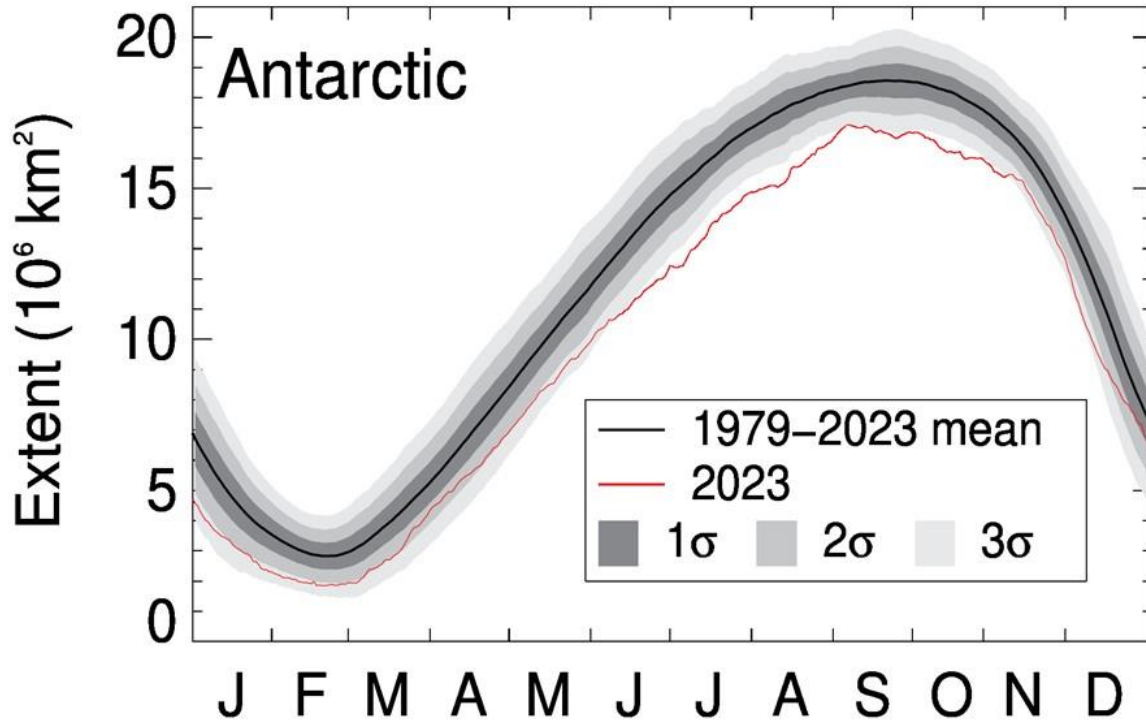


Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

Note: Mean (black line) calculated from data between 1979 and 2022; grey areas represent 1, 2 and 3 standard deviations (σ) around the mean for the same time period; data from 2023 are also shown to illustrate recent changes.

Figure II

Seasonal mean sea-ice extent in the Antarctic and its variability

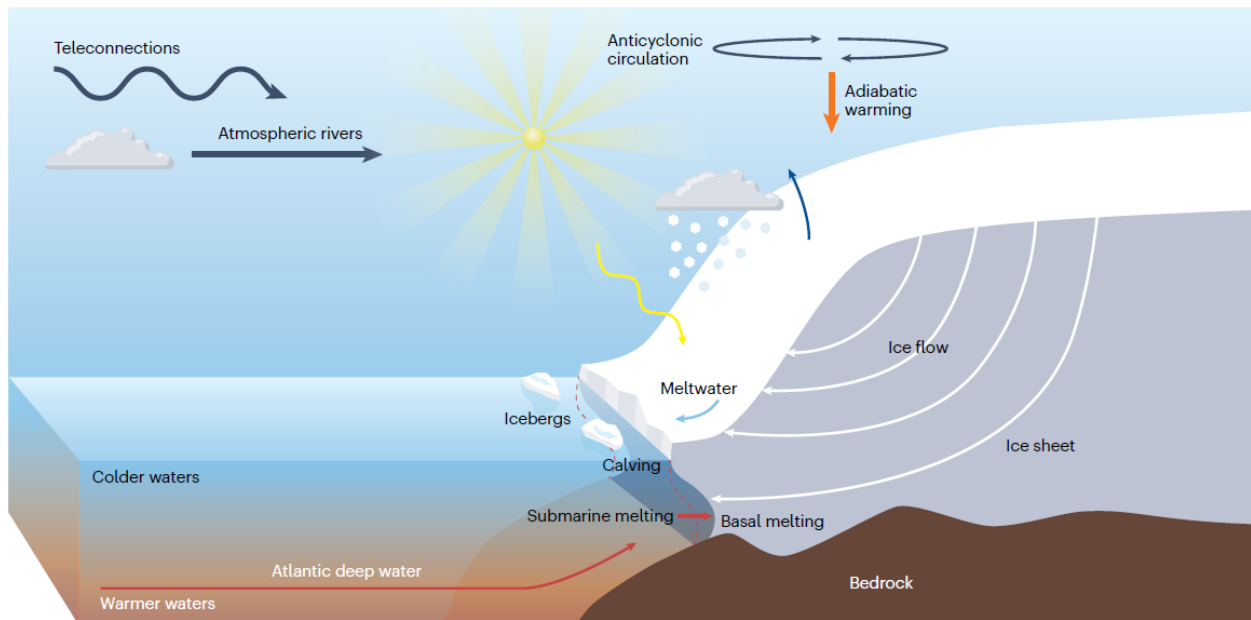


Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

Note: Mean (black line) calculated from data between 1979 and 2022; grey areas represent 1, 2 and 3 standard deviations (σ) around the mean for the same period; also shown are the data from 2023 to illustrate recent changes.

Figure III

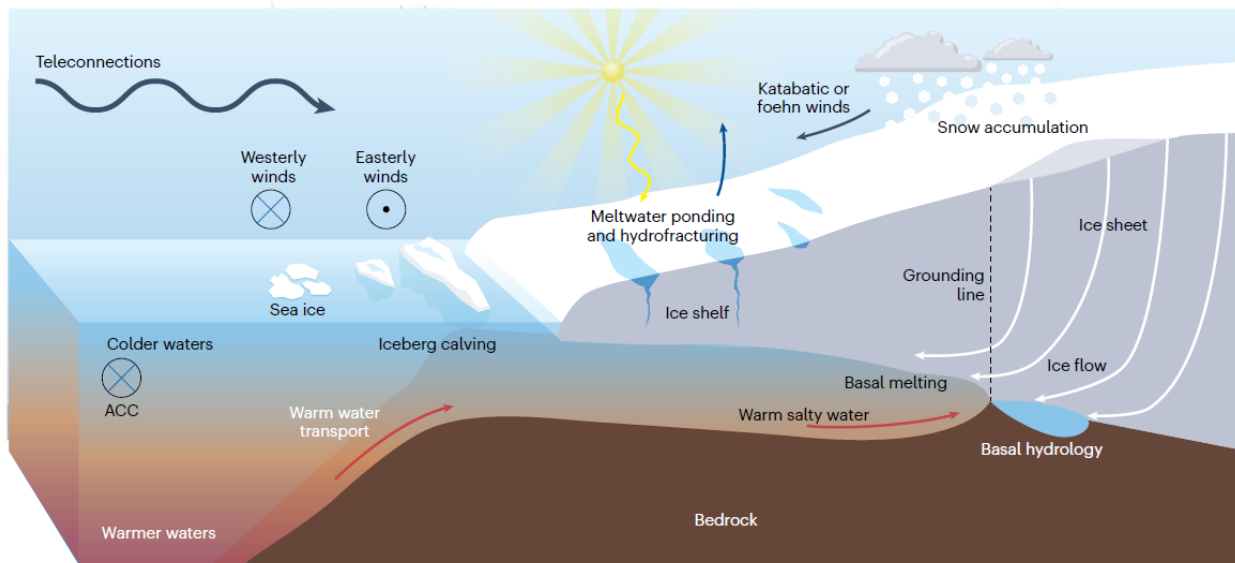
Processes responsible for changes in ice in the Greenland ice sheet



Source: Hanna and others, 2024.

Figure IV

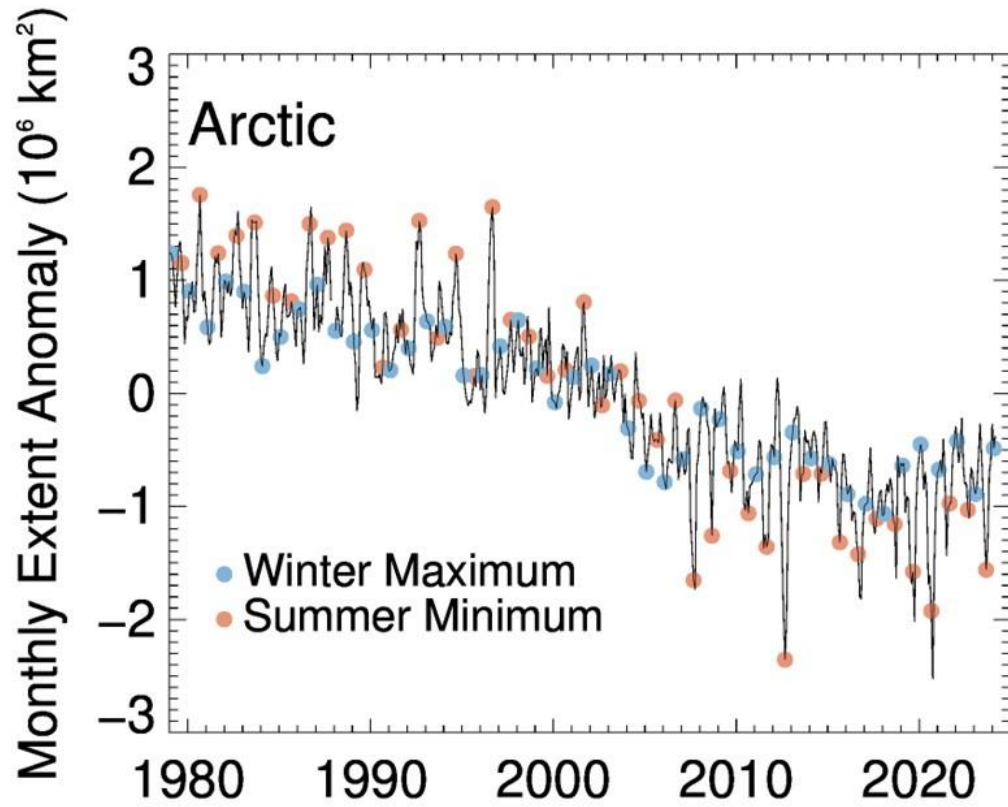
Processes responsible for changes in ice in Antarctic ice sheets



Source: Hanna and others, 2024.

Figure V

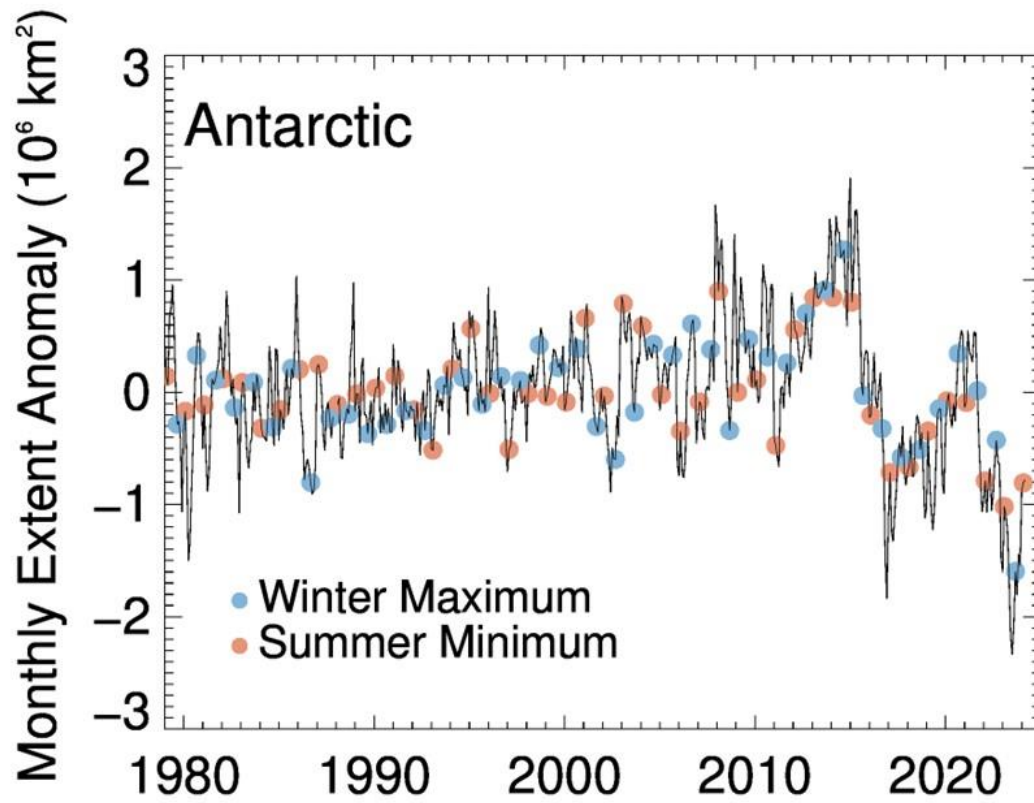
Annual Arctic sea-ice extent since 1979



Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

Figure VI

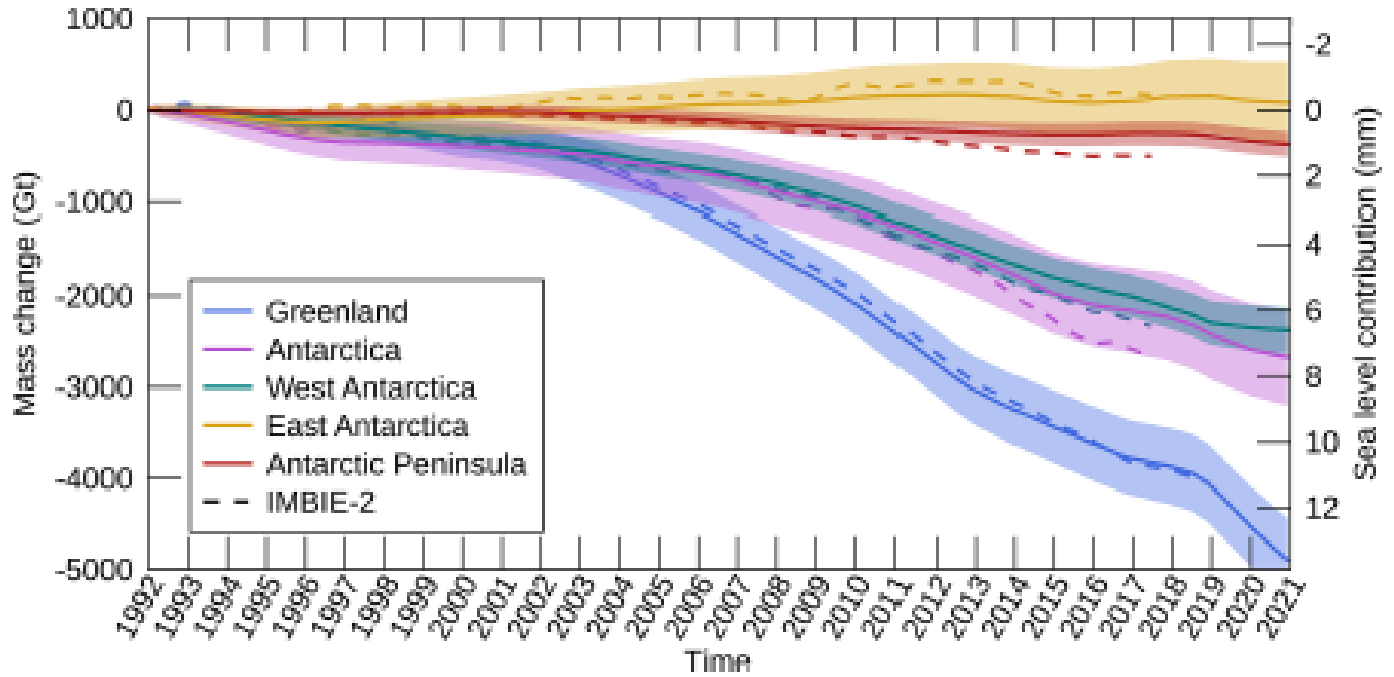
Annual Antarctic sea-ice extent since 1979



Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

Figure VII

Cumulative ice sheet mass changes for ice sheets in Greenland and Antarctica



Source: Otsaka and others, 2023.

Note: Shaded areas represent the associated uncertainties and are calculated according to Otsaka and others (2023) and dashed lines show the results from the Ice Sheet Mass Balance Intercomparison Project Team (2020).