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Chapter 6

Antarctic sea ice and climate change

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Summary

The Antarctic sea ice is only approximately 1 m thick, but in winter, it covers an area of up to 18.5 million km^2. Most of the ice melts every summer. Antarctic sea ice acts as a strong insulator between the warmer ocean and colder atmosphere, and in daylight seasons efficiently reflects solar radiation. Antarctic sea ice plays a crucial role in the global climate system and has exhibited complex, regionally variable changes over the past decades. Unlike the Arctic Sea ice, which has consistently declined, Antarctic Sea ice experienced a slight increase from 1979 to 2014, followed by a sharp decrease since 2015, raising concerns about a long-term downward trend. Predicting future trends is challenging due to limited pre-satellite data, high variability, and the interplay of natural and anthropogenic factors. Model biases, especially in ice thickness and drift, further complicate projections, though CMIP6 models show modest improvements over CMIP5. The anticipated sea ice decline in the Southern Ocean will have profound regional and global impacts. Reduced sea ice will decrease surface albedo, amplifying atmospheric warming and moistening, while altering water mass transformation, Antarctic Bottom Water (AABW) formation, and ocean circulation. These changes could modify the Southern Ocean stratification and meridional overturning circulation, and promote oceanic heat transport toward the Antarctic ice sheet.

Keywords:

Sea ice extent, thickness and concentration

Sea ice growth and melt

Sea ice dynamics

Attribution of sea ice changes

Southern Annular Mode

Meridional Overturning Circulation

1. Introduction

In winter, sea ice covers an area of up to 18.5 million km^2 in the Southern Ocean, while in summer it shrinks to some 2.5 million km^2 [1] (Figure 1). As a vast majority of the ice melts every summer, most ice only experiences a single growing season, which restricts the maximum ice thickness. Thicker multi-year ice occurs in small regions, such as the southwestern Weddell Sea, where the prevailing drift patterns pack the ice against the continent and ice shelves. On average, the ice thickness in the Southern Ocean is only some 0.9 to 1.1 m [2], and the snow depth on sea ice is typically some 0.2 m for first-year ice and 0.5 m for second-year ice [3]. The thinnest ice is generally found in the Amundsen and Bellingshausen Seas and thicker ice in the Weddell and Ross Seas. In addition to regional variations, sea ice thickness varies seasonally and interannually [4]. Also, the sea ice concentration, i.e., the fraction of the sea surface covered by ice, varies a lot. Close to the Antarctic continent are regions of land-fast ice, which does not drift and has practically 100% concentration. In the drift-ice zone, sea ice concentration is typically lower, gradually decreasing to zero towards the northern margin of the sea-ice zone.

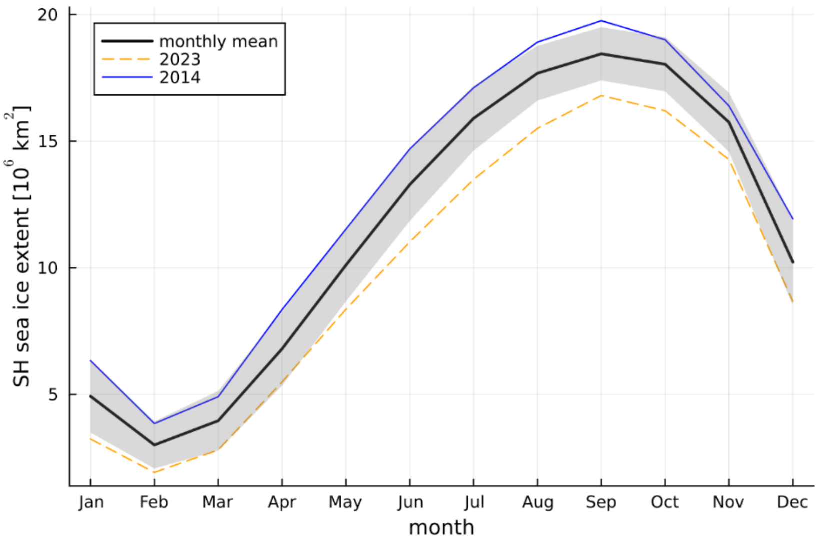

Figure 1. The 1979-2023 Antarctic sea ice extent mean (black line) and the region bounded by two standard deviations (grey shading). The blue line shows the record high 2014 sea ice extent, and the dashed orange line shows the record low 2023 sea ice extent (Data source: [1]).

Accordingly, sea ice thickness is controlled by both thermodynamic and dynamic processes. Convergent motion of thin ice floes results in rafting, i.e., the floes pile on each other, whereas in the case of thicker floes, convergence generates ridging [5]. Common occurrences of ice ridges and sastrugi (snow dunes) characterize the surface topography of Antarctic sea ice. The build-up of ridges is associated with the build-up of keels, which dominate the bottom topography (draft) of Antarctic sea ice [6]. Due to the hydrostatic balance, keels are about 5 to 6 times thicker than sails, the parts above the water surface [7]. The dynamic thickening of sea ice makes it more resilient to summer melting. Keels also support organisms like algae that live within the ice [8].

The areas of open water in the sea ice zone include fractures, cracks, leads, and polynyas. Leads are narrow, elongated areas of open water. They form due to divergent ice drift and close due to convergent drift, driven by winds and ocean currents. Individual leads typically remain open only for a day or less. Polynyas are more persistent and larger areas of open water within the sea ice zone [9]. In cold seasons, large amounts of ocean heat are released into the atmosphere via leads and polynyas. Hence, much of the new ice production occurs in leads and polynyas [10]. Leads and polynyas are also important for marine ecosystems [11].

Compared with the Arctic, the range of seasonal variation of sea ice extent is much larger in the Antarctic. Also, sea ice concentration in the Antarctic is, on average, lower than in the Arctic. The large seasonal variations and the low sea ice concentration are largely because there are no surrounding continents restricting the wintertime sea ice expansion in the Antarctic. Hence, sea ice drift in the Antarctic is, on average, divergent, towards wider latitudinal belts in northern parts of the Southern Ocean.

The Antarctic sea-ice zone is an important, dynamic component of the global climate system. Due to the large area covered by the highly insulating sea ice and the snowpack on top of it, the hemispherical-scale heat loss from the ocean to the atmosphere is strongly reduced in the cold seasons. In daylight seasons, a large portion of solar shortwave radiation is reflected back to space, reducing the net solar radiation received by the Earth [12]. Understanding Antarctic sea ice is vital for studies on the global climate, as Antarctic sea ice and its changes influence the planetary-scale energy budget, distribution of heat between the ocean and atmosphere, and further the large-scale circulation in the ocean and atmosphere.

However, the sources of information on Antarctic sea ice are limited. These include surface-based observations from research vessels [13, 14], buoys and other autonomous devices deployed on ice floes [15], coastal stations [16, 17], drifting ice stations [18, 19], and autonomous underwater vehicles [6]. Ship-based observations are mostly restricted to summer, and there have been only a few drifting sea ice stations in the Antarctic. Hence, a major part of data on the Antarctic sea ice is based on satellite remote sensing. Its key components include passive microwave remote sensing of sea ice extent and concentration [20], radar and lidar altimetry on sea ice thickness and freeboard and snow depth [2], and laser altimetry on sea ice freeboard [21]. The ice type can be identified by combining radar and passive microwave remote sensing [22]. In addition, limited amounts of remote sensing data are available from research aircraft campaigns [23]. Direct and comprehensive observations of the Southern Ocean temperatures in the top two kilometres have been available only since 2004, when the Argo program began [24]. Moreover, analyses of hydrographic measurements combined with satellite altimeter measurements starting in the 1990s have provided estimates of changes in the ocean heat content.

In addition to in-situ and remote sensing observations, an important source of information is atmospheric and ocean reanalyses, which assimilate available observations into numerical models and yield analyses on a regular grid. Although reanalysis products cover more than 100 years, their results for the Antarctic are more reliable from 1979 onwards, since when satellite data have been assimilated into the models. However, ocean reanalyses have had a large spread in the Southern Ocean still in recent decades [25].

2. Observed changes

2.1 Observed changes in the Antarctic atmosphere and ocean

Climate warming in the Antarctic includes large spatial variations. While the West Antarctica has warmed fast, the warming rate in East Antarctica has been much slower, even including regions with slight cooling trends. The trends in air temperature are closely associated with those in precipitation (rain + snowfall). Observations, atmospheric reanalyses and climate model experiments suggest increased precipitation over the Antarctic, with a typical sensitivity of 5 – 10% increase per 1 K increase in air temperature [26].

Estimates of the Southern Ocean subsurface warmign include large uncertainties, but the available observations suggest that the warming over the period 2004-2018 emerges from interannual variability [27] (Figure 2), and the Southern Ocean has warmed faster than other oceans, especially in the abyss [28]. Neither the trends in near-surface air temperature over the Southern Ocean are well known. Various atmospheric reanalyses suggest different spatial patterns and even regionally opposing signs of air temperature changes over the Southern Ocean (Figure 3). The scatter in the temperature trends is supposed to be due to (a) sparsity of observations on near-surface air temperature, (b) challenges in accurately simulating it in conditions of prevailing stable stratification over sea ice [29], and (c) oversimplification in the presentation of sea ice and snow thermodynamics in models applied in the production of atmospheric reanalyses [30, 31]. Due to fewer issues related to (c), we consider the NCEP-CFSR products more reliable than those of ERA5 [32].

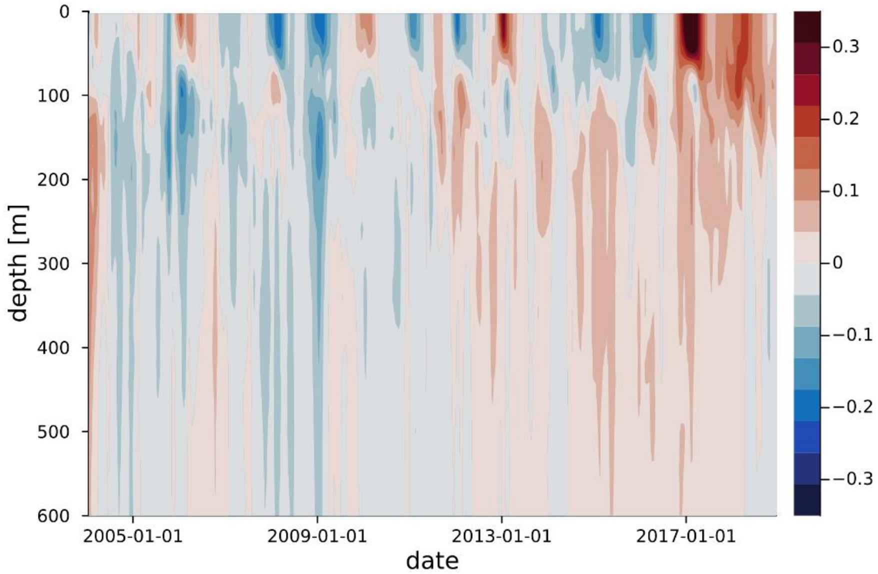

Figure 2. Zonal mean monthly ocean temperature anomaly (colour codes in ºC) time series between 50-65°S from 2004 to 2018 relative to 2004-2018 monthly means. Data are from Roemmich-Gilson Argo Climatology [24].

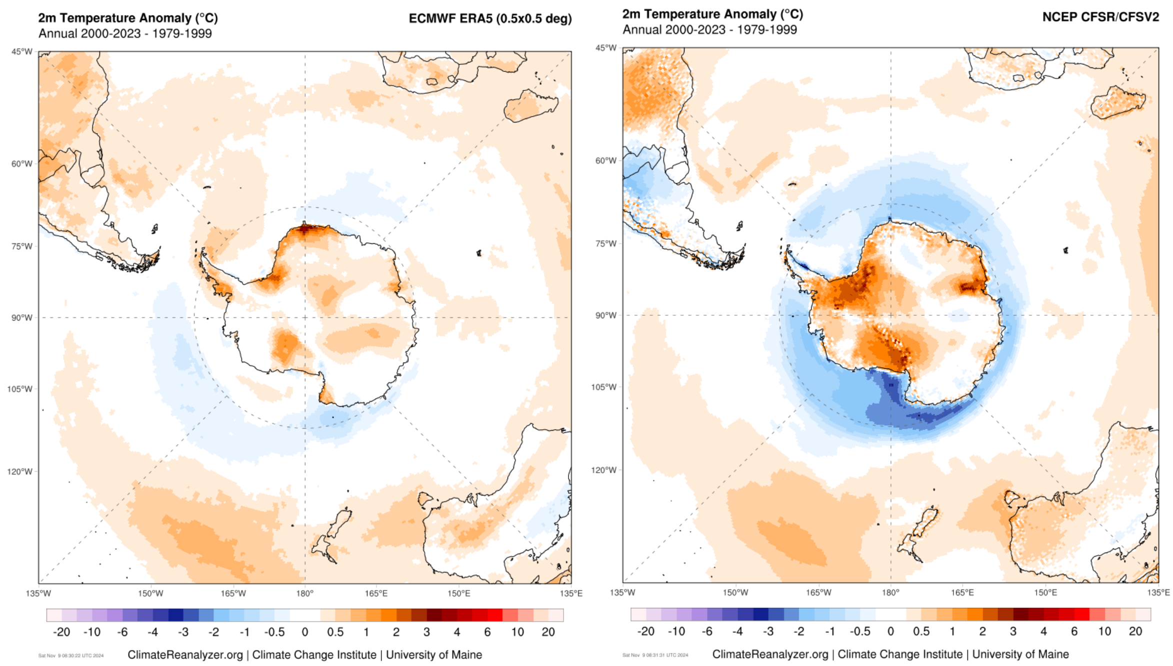

Figure 3. Differences in T2m over the Antarctic between periods of 2000-2023 and 1979-1999 according to ERA-5 (left) and NCEP-CFSR (right) reanalyses. The figure was prepared using ClimateReanalyzer.org of the University of Maine.

Considering zonal mean values over the Southern Ocean between 60 and 70ºS, the NCEP-CFSR reanalysis suggests a decreasing 2-m air temperature (T2m) trend from 1979 to 2010, followed by a rapid increase (Figure 4a). Precipitation shows large interannual variations and a general decrease from 1979 to 1994, followed by a strong increase (Figure 4b). Zonal winds over the Southern Ocean show large interannual variations, with a weak but significant ($p < 0.05$) increasing trend during 1979-2023 (Figure 4c) whereas meridional winds show a comparable decreasing trend (Figure 4d).

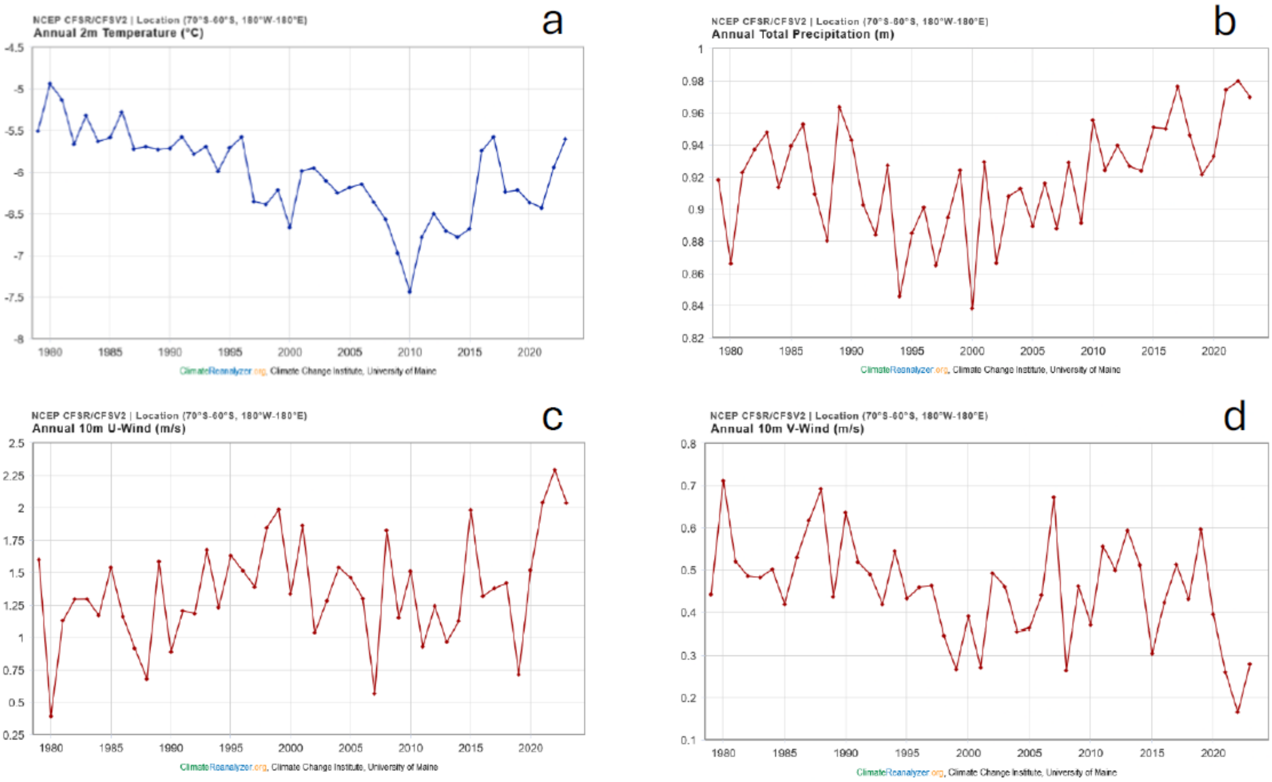

Figure 4. Time series of annual mean values of (a) T2m, (b) precipitation, (c) 10-m zonal wind, and (d) 10-m meridional wind, averaged over latitudinal belts of 60-70ºS, based on NCEP-CFSR reanalysis. The figure was prepared using ClimateReanalyzer.org of the University of Maine.

Much of the trends and variations in the Antarctic atmosphere and ocean are related to the Southern Annular Mode (SAM), which represents the strength and north-south shifting of the westerly wind belt encircling Antarctica. The positive phase of SAM, when the zonal winds are strong and shifted southwards, favours cold conditions and reduced precipitation over Antarctica, except in the Antarctic Peninsula and surrounding sea ice zone. During the negative phase of SAM, the Southern Ocean storm track shifts northwards, enabling more meridional flow patterns to carry warm, moist air masses to the Antarctic [33]. Further, the SAM affects currents and upwelling patterns in the Southern Ocean, affecting nutrient distribution, biological productivity, and the upwelling of warm Circumpolar Deep Water, which can contribute to glacial melt along the Antarctic Ice Sheet [34].

The SAM has displayed a general positive trend since the late 1970s, particularly in summer. Since the late 1990s, however, the trend has weakened, although SAM has remained positive overall (Figure 5). During spring and autumn, SAM exhibits moderate positive trends but also experiences inter-annual variability. In winter, SAM shows less of a long-term trend and more inter-annual variability. The Amundsen Sea Low (ASL) is a large-scale pressure pattern closely associated with SAM. A stronger (weaker) ASL occurs during the positive (negative) SAM phase and, accordingly, ASL has become stronger during recent decades.

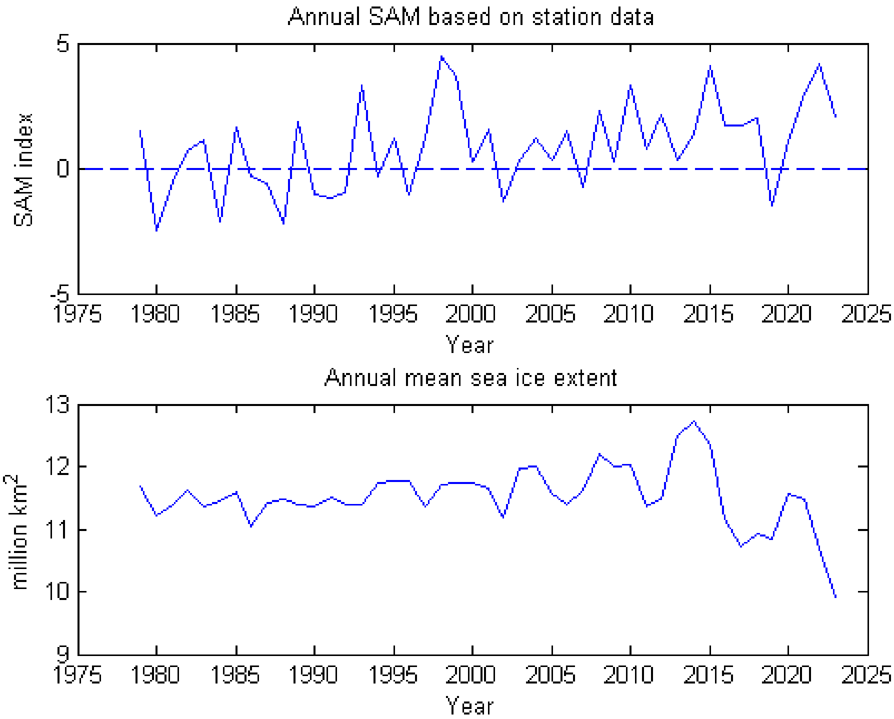

Figure 5. Time series of the annual mean values of SAM based on station observations (upper panel), calculated following [35], and sea ice extent in the Southern Ocean (lower panel). The SAM data are from the British Antarctic Survey, http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.1957.2007.seas.txt, and the sea ice extent data are from the sea ice portal of the Alfred Wegener Institute and collaborators, https://data.meereisportal.de.

2.2 Observed changes in Antarctic sea ice

We focus on the period since 1979 when reliable regular circumpolar information on the extent and concentration of Antarctic sea ice is available. The first part of the period, from 1979 to 2014, was characterised by a slow increase in sea ice extent with an average rate of 1.5% per decade [36], (Figure 5b). Another interpretation of the trends is that the first period without a trend spans until August 2007, followed by increased sea ice from 2007 until 2014, and a third period with decreased sea ice since 2016 [37]. In any case, the increase of sea ice extent occurred in most of the sea ice zone, and was the strongest in the Ross Sea region [38]. However, in the Bellingshausen and Amundsen seas, the sea ice extent has shown decreasing trends already since 1979, and the decline has accelerated since the late 1990s [39]. The circumpolar sea ice extent turned to decline after 2014 [40], the decreasing trend being the strongest in the Bellingshausen and Amundsen seas as well as parts of the Weddell and Ross seas [41]. The last one is notable, as the Ross Sea primarily contributed to the overall increase in Antarctic sea ice until 2015. All the above-mentioned trends are superimposed by a large interannual variability.

The years of most extreme sea ice extent have been 2014 (record maximum) and 2023 (record minimum), which deviated by more than two standard deviations from the mean conditions over 1981-2010 (Figure 1). The negative anomaly in 2023 was particularly large in austral winter and spring.

Antarctic sea ice thickness and volume trends are not well known due to limited observations, but they may have slightly increased along with the rise in ice extent from 1979 to 2014 [42]. Since 2015, the reduction in sea ice extent likely corresponds to a decline in sea ice thickness and volume. Changes in sea ice have occurred simultaneously with changes in the atmosphere and ocean.

3 Projected climate change

3.1 Projected changes in the Antarctic atmosphere and ocean

Based on climate model experiments, major warming is expected in the Antarctic region by the end of the 21st century, although with considerable regional variations. In the high-emission scenarios (RCP8.5 and SSP5-8.5), T2m may increase by 3–6°C in large parts of Antarctica and the Southern Ocean [43]. The strongest warming is expected in the Antarctic Peninsula and West Antarctica [44]. In a warmer climate, the moisture-holding capacity of the atmosphere will be larger, resulting in an intensified hydrological cycle. Projections suggest that by 2100 Antarctic precipitation may increase by 10–20%, with the greatest increases over coastal and low-elevation regions [45] and the sea ice zone [43]. Most of the precipitation will in any case fall as snow but the fraction of rain will increase in the above-mentioned regions.

Potential changes in atmospheric circulation patterns are more uncertain than those in temperature and precipitation. However, climate models suggest that SAM will remain in a predominantly positive phase due to greenhouse gas forcing [43]. The dominance of the climate warming effect would strengthen westerly winds around Antarctica, isolating the region and limiting warm-air intrusion from the north. However, in coastal areas, this shift may cause increased upwelling of warmer ocean water, accelerating the melt of sea ice and ice shelves [46].

So far, the zero-degree isotherm latitude has been migrating southward, with major implications for the cryosphere, sea ice, and marine ecosystems in terms of their productivity and phenology. Further southward migration is expected, with rates depending on emission scenarios [47]. The migration rate is faster for climate predictions under the high emission scenario SSP5-8.5 than under the lower one SSP2-4.5.

The Southern Ocean circulation and heat distribution are sensitive to changes in dynamic and thermodynamic atmospheric forcing and meltwater discharge from the Antarctic ice sheet. Future projections remain uncertain due to the complexity of the coupled atmosphere-ice-ocean system processes, which are incompletely represented in climate models [43]. In any case, the Southern Ocean warming pace and associated changes depend on future emissions.

3.2 Projected changes in Antarctic sea ice

Both [48] and [43] assessed a low confidence in future projections of Antarctic sea ice. This is related to uncertainties in the projected mitigation of the sea-ice loss by stratospheric ozone recovery [49, 50] and by an increased freshwater input from the melting of the Antarctic ice sheet [51]. Further, there are uncertainties related to a limited agreement between historical model simulations and observations, limited reliable observations on a process level, and a lack of process understanding of the substantial spread in CMIP5 and CMIP6 model simulations.

In addition, the future changes in Antarctic sea ice are highly sensitive to greenhouse gas emission scenarios, affecting the atmospheric and oceanic warming rates. Under high-emission scenarios

(SSP5-8.5 and RCP8.5), substantial declines in both extent and thickness of sea ice are expected by the end of the 21st century. These scenarios predict a global mean warming of 4–5°C and more at higher latitudes, driving rapid sea ice loss of 25–50% by the end of the 21st century [48]. In summer, the reduction in sea ice extent may be even larger in releative numbers, resulting in a nearly ice-free Southern Ocean by 2100. Regional differences in sea ice trends are expected to persist, with the Bellingshausen and Amundsen Seas experiencing more rapid declines in sea ice due to higher ocean temperatures and stronger atmospheric warming in these regions. According to [52], sea ice is expected to decline, at a lower rate in the Ross Sea, where it expanded most in the past decades. In addition, sea ice in the Southern Ocean will become thinner.

Under medium-emission scenarios (SSP2-4.5 and RCP4.5) greenhouse gas emissions peak around mid-century and thereafter gradually decline. An approximately 20 to 30% reduction in sea ice extent by the end of the century is expected [48]. The sea ice cover may reach a new stable state rather than continuing unabated loss, especially if atmospheric GHG concentrations stabilize. This scenario could allow for some seasonal sea ice recovery in winter, although summer ice would still be substantially reduced.

Under low-emission scenarios such as SSP1-2.6 and RCP2.6, which are consistent with significant mitigation efforts and a global warming limit of 1.5 to 2°C, much smaller declines in Antarctic sea ice extent and thickness are projected. These pathways suggest that substantial GHG reductions could largely preserve the current extent of Antarctic sea ice, especially in winter [53].

4. Drivers of changes in Antarctic sea ice

Variations in Antarctic sea-ice conditions are driven by atmospheric and oceanic forcing factors. To better understand the reasons for the observed and projected changes, we first introduce the physical processes of interactions between the atmosphere, snow, sea ice and the ocean.

4.1 Physical processes

4.1.1 Dynamic forcing by the atmosphere and ocean

Momentum balance and mass continuum determine sea-ice dynamics [54]. Here, the drift ice material consists of separate ice floes and open water between, so that the areal coverage of drift ice per unit area is its concentration, and its volume, or the effective thickness, is the total volume of all ice floes divided by the unit area [55].

The air-ice momentum flux depends on the difference between the wind and ice drift vectors and on the air-ice drag coefficient, and analogously for the ice-water momentum flux. The air-ice and ice-water drag coefficients depend on the ice/snow surface and ice bottom topographies (dominated by sastrugi, ridges and keels), respectively, and on the stratification in the atmospheric surface layer and the oceanic surface and Ekman layers. Drag coefficients are larger in well-mixed surface layers than in stably stratified ones.

In regions where the sea ice concentration is approximately 80% or lower, the effects of internal resistance of the ice pack can be ignored, and the ice drift follows the free drift concept [56, 57]. In such conditions, the drift results from the balance of air-ice and ice-water momentum fluxes, the Coriolis force, and the gravitational force due to sea-surface tilt, resulting in thin ice drift with a speed of 2 to 3% of the wind speed, with the drift vector deviated some 30 degrees to the left of the wind vector [58]. However, if the ocean current is strong or ice thick, the numbers may differ.

In the Southern Ocean, circumpolar westerlies dominate, and the 30-degree deviation angle favours divergent ice drift and northward expansion of the ice cover. However, the effect is complex and varies regionally, often leading to increased SIC in certain areas and decreased in others. On smaller spatial scales, transient cyclones strongly interact with sea ice conditions. Synoptic-scale cyclones modify the ice field, resulting in rapid changes in SIC, whereas mesoscale cyclones, including Polar lows, are affected by the distribution of SIC, gaining energy via large turbulent surface fluxes from the areas of open water [59]. In addition to sea ice concentration, wind forcing affects sea ice thickness as well as the occurrence of sastrugi, ridges, keels and leads.

Ocean surface waves impact sea-ice dynamics by breaking ice floes into smaller ones and weakening the ice, making it more prone to deformation. Under the wave action, ice floes collide, lose kinetic energy, erode at their edges, and become fragmented floes, brash or pancake ice [60]. In the process, the ice roughness changes, which impacts the air-ice and ice-ocean drag coefficients. The impact of ocean waves is high, especially in the marginal ice zone, where the sea-ice concentration is typically between 15% and 80%. This zone can be hundreds of kilometres wide in the Southern Ocean, where the swell can penetrate deep into the sea ice pack [61].

Along a large part of the Antarctic coastline and ice shelf margins, vigorous south-easterly winds favour the opening of coastal polynyas [62, 63]. These are so-called latent heat polynyas [64], which generate copious amounts of ice, and at the same time, the high oceanic heat loss and salt flux from new ice to the ocean produce cold and high salinity water. Simultaneously, the variability and properties of the upwelling Circumpolar Deep Water impact the formation of sea ice in the coastal polynyas [65].

4.1.2 Thermodynamic forcing by the atmosphere and ocean

The surface melt of sea ice is controlled by the surface energy budget, which consists of downward and upward components of solar shortwave and thermal longwave radiation, the turbulent fluxes of sensible and latent heat, and the conductive heat flux through the ice and snow [66]. Occasionally also precipitation and washing by ocean surface waves generate heat flux to ice surface. The turbulent surface fluxes are controlled by the wind speed and the air-surface differences in temperature and specific humidity [67], whereas the radiative fluxes are strongly affected by clouds, which enhance downward longwave radiation and reduce downward shortwave radiation [68]. The melting of sea ice reduces the region's reflectivity (albedo), allowing more solar energy absorption by the ocean. This feedback loop amplifies warming and sea ice loss, especially in regions experiencing consistent reductions in sea ice cover. However, the effects of albedo feedback have in general been more pronounced in the Arctic, as Antarctic sea ice trends have been more variable and spatially heterogeneous [69], and the Antarctic sea ice melt is more affected by basal than surface melt [70].

The basal melt occurs when the heat flux from the ocean to ice base exceeds the conductive heat flux from the ice base to the surface. This is a typical situation in summer, when the ice layer is almost isothermal. In autumn and winter, the ice surface is usually much colder than the ice base, generating a large in-ice conductive heat flux, which typically exceeds the basal heat flux from the ocean. Hence, basal growth occurs [71]. The basal heat flux depends primarily on oceanic stratification and the ice-ocean stress, which determine the turbulent mixing efficiency of heat. During melting, the mixed layer under the ice is typically shallower than during freezing, due to the opposing buoyancy fluxes related to meltwater and salt rejection, respectively [72].

Antarctic sea ice also grows via snow-to-ice transformation. In summer, due to basal melt of ice, the ratio of snow depth to ice thickness often becomes so high that the ice surface is pressed below the sea surface. This results in flooding, when seawater mixes with the lower part of the snowpack. The resulting slush often freezes so that part of the snowpack is transformed into granular ice, called snow ice [73]. Another mechanism of snow-to-ice transformation is formation of superimposed ice via snow melt, percolation of meltwater to the snow-ice interphase, and refreezing there [74]. Also, rain may percolate to the snow-ice interphase and freeze there.

Unlike the latent heat polynya kept open by wind forcing (Section 4.1.1), the so-called sensible heat polynya is an area within the sea ice pack kept open by upwelling oceanic heat that completely melts sea ice away [64]. Upwelling can be local and related to subsea topographic features, for example Maud Rise, from which the Weddell Sea polynya emerged downstream in three years of the 1970s [75].

4.2 Attribution of the observed changes in sea ice

Antarctic sea ice is highly variable from year to year and has been influenced by both the global warming and natural variability of atmospheric and oceanic conditions [52]. This complicates the attribution of trends.

The increasing trend in the Antarctic sea ice extent from 1979 to 2014 is generally attributed to the dominance of the positive phase of SAM. It increases the northward Ekman transport of sea ice and reduces ocean surface temperatures, thus increasing the sea ice extent. However, the impact of SAM on sea ice is complex. Although generally favouring a large ice extent, positive SAM with stronger westerlies has had mixed effects on sea ice, promoting expansion in some areas, such as the Ross Sea, and reduction in others [76, 77]. The reduction may be associated with regionally enhanced ocean upwelling [69, 78]. Also, over the Bellingshausen and Amundsen Seas, strong westerlies over the sea-ice zone are often related to airmass origin from the northwest, carrying warm air masses to melt sea ice.

Negative SAM anomalies are often associated with warm anomalies in sea surface temperatures, which was the case of the 2017 (then) record minimum sea ice extent [79]. However, the 2022 and 2023 record sea ice minima occurred with anomalously positive SAM phases and thus cannot be explained by the SAM phase as earlier. This change in the sea ice behaviour has been, at least partially, linked to subsurface Southern Ocean warming [37], probably amplified by atmospheric forcing [80, 81]. The shortening of the ice season has accelerated the post-2015 sea ice decline, with the thermodynamics of the ocean mixed layer and sea ice as well as the ice-albedo feedback playing a central role [82]. Since 2016, the Antarctic sea ice decline has even strongly contributed to the global snow and ice albedo feedback [83]. The strong sea ice decline since 2016 and the exceptional ice seasons in 2022 and 2023 may mark the beginning of a new Antarctic sea ice state or remain anomalous, for example, due to the system's internal variability.

The strong positive SAM trend in summer has been largely due to the impact of stratospheric ozone depletion, which is the strongest in summer, creating a pronounced poleward shift and strengthening westerly winds [76]. Ozone depletion has less influence on the SAM during winter due to weaker sunlight, which limits its impact on stratospheric temperatures. Consequently, wintertime SAM variability is more influenced by natural climate variability, such as ENSO. El Niño events are typically associated with a negative SAM phase, while La Niña events tend to co-occur with a positive SAM phase. This relationship introduces inter-annual variability to the SAM, superimposed with the above-mentioned trends. In addition to ozone depletion, positive SAM has been attributed to increased greenhouse gas concentrations [84].

Considering inter-annual variations, Antarctic sea ice is affected by several teleconnections originating from the tropics. The El Niño-Southern Oscillation (ENSO) in the tropical Pacific affects Antarctic sea ice through teleconnections that alter atmospheric circulation and temperature patterns. El Niño events are generally associated with warmer conditions in the Bellingshausen and Amundsen Seas, contributing to sea ice reduction in these areas. In contrast, La Niña events tend to promote cooler conditions and sea ice growth, particularly in the Ross Sea [85]. ENSO events also contribute to the Antarctic Dipole, a pattern of opposing sea ice conditions between the Pacific and Atlantic sectors of the Southern Ocean. This dipole effect is particularly evident during strong El Niño or La Niña events and has contributed to regional variability in Antarctic sea ice [86]. The impacts of ENSO and SAM on sea ice extent vary seasonally, being strongest in autumn [87].

Zonal Wave Three (ZW3) is a major feature of the Southern Hemisphere large-scale atmospheric circulation, affecting momentum and heat transport to the Antarctic, which makes it important for sea ice dynamics and thermodynamics [88]. In the three regios of cold equatorward flow the ocean loses more heat, and sea ice growth and expansion is greater, while the reverse occurs in the three regions of warm poleward flow. Although previously thought to be affected by the South American, African and Australian landmasses, according to [89] ZW3 is predominantly driven by zonally asymmetric deep convection in the tropics. Tropical convection is affected, among others, by the stratospheric Quasi-Biennal Oscilaltion and the Madden Julian Oscillation, and the effects of tropical convection activity are transmitted to the Antarctic sea ice zone by planetary wave trains [90]. Patterns of planetary wave trains linking tropical convection and related SST anomalies to Antarctic sea ice include the Pacific South American Pattern (PSA) and the South Pacific Oscillation [91]. Some of the varability of Antarctic sea ice conditions is also associated with the Antarctic Circumpolar Wave, which circles the Southern Ocean in approximately eight years [92], being partly driven by ENSO, mediated by PSA and SAM.

Further, the Indian Ocean Dipole (IOD), a tropical climate mode, influences Antarctic sea ice by altering atmospheric wave patterns. Positive IOD events, characterized by warmer western Indian Ocean SSTs, can lead to warmer and drier conditions in the Southern Hemisphere, reducing sea ice extent in areas such as the Weddell Sea. Conversely, negative IOD events can support sea ice growth by enhancing cool air flow toward Antarctica [93]. In addition, a teleconnection has been suggested between positive SST anomalies over the southeastern Indian Ocean and the western tropical Pacific Ocean and an increase in the Antarctic sea ice extent during 1979-2020, and the opposite for negative SST anomalies [94].

SAM and atmospheric teleconnections affect Antarctic sea ice mostly on interannual time scales, but changes in the ocean affect sea ice on decadal to centennial scales, i.e., time scales comparable to those of climate warming and recovery of the ozone layer. The key oceanic drivers are changes in upwelling and freshening of the ocean surface layers via increased meltwater from ice shelves and the ice sheet [95]. In addition to surface freshening, the salinity below the surface layer increases due to brine rejection from freezing. Together, these two effects result in a more stable water column, which inhibits upward oceanic heat flux, promotes ice growth, and slows down its melting. However, compared to many other ocean regions, the Southern Ocean is relatively weakly stratified, and under suitable circumstances, the upwelling of oceanic heat, as a part of the overturning circulation, can limit the sea ice growth and extent. The northward Ekman transport and upwelling are opposing processes from the sea ice perspective but act on different time scales. The transport effect is instantaneous compared to upwelling, which manifests on decadal time scales [96]. It has been hypothesized that the transport effect dominated before 2016 but has since been taken over by upwelling [97]. The eddy compensation in the Antarctic Circumpolar Current opposes the wind-driven upwelling and might delay this change [97].

Despite of the complexity of the natural variability and effects of the ozone depletion, in the background the greenhouse-gas induced global warming is progressing. The rapid sea ice decline since 2016 may indicate that long-term warming trends in the atmosphere and ocean are beginning to outweigh the forces that previously promoted sea ice stability or growth [36, 98]. The post 2016 decline might also be a tipping point where the Antarctic sea ice has reached a new state rather than a gradual change. This assumption is supported by increased sea ice variability before 2016 (Figure 5 lower panel). It could be explained by the subsurface ocean warming (Figure 2) that has overcome the increased northward Ekman transport of sea ice.

4.3. Attribution of the projected changes in sea ice

The projected changes in Antarctic sea ice by the end of the 21st century are supposed to be mostly driven by the same mechanisms as the observed changes, but the strength of the various mechanisms may change. Above all, the warming of the ocean and atmosphere due to rising greenhouse gas concentrations will have an increasingly large role. The Bellingshausen and Amundsen Seas are regions where sea ice loss is considered particularly sensitive to the warming trend. The direct effects of warming are expected to dominate, particularly under the high-emission scenarios [90].

The direct thermodynamic drivers of sea ice melt will be amplified by positive feedbacks, such as the ice-albedo feedback (Section 4.1.2). It is expected to amplify summer sea ice loss and contribute to warmer surface temperatures. This effect is more pronounced under high-emission scenarios, where rapid warming triggers more sea ice loss, leading to self-reinforcing cycles of melting [99]. Further, under atmospheric warming, the prevailing air temperature inversion (temperature increases with height) over Antarctica is projected to weaken, which will reduce the stable stratification in the cold air mass near the surface. This might result in a rapid increase of near-surface temperatures, enhancing ice melt in summer and reducing ice growth in winter, particularly near coastal regions [100].

In addition to the direct thermodynamic effects, the oceanic and atmospheric warming will affect sea ice indirectly by altering circulation patterns. Climate models project a continued strengthening of the circumpolar westerly winds around Antarctica driven by the climate warming, which will probably dominate the effect of the expected recovery of the stratospheric ozone layer. Accordingly, SAM will probably not turn into the negative phase. The effects of the positive phase of SAM will be qualitatively similar as those observed in the past (Section 4.2), including dynamic expansion of the ice field in most regions, although around the coast the positive SAM favours ice melt by enhancing upwelling of warm water onto the continental shelf [46, 84]).

Teleconnections affecting Antarctic sea ice (Section 4.2) are expected to be active also in the future. It is suggested that possible future intensification of climate modes, such as ENSO and IOD, could amplify sea ice variability in the Antarctic [101]. A stronger Antarctic Dipole is projected to create regional contrasts in sea ice conditions, with reductions in the Amundsen-Bellingshausen Seas and potential gains in the Ross Sea, although overall net sea ice loss is expected [102].

5. Discussion

The Antarctic sea ice zone is an important, sensitive component of the global climate system. The changes in Antarctic sea ice over the past 50 years have been influenced by a complex interplay of atmospheric and oceanic drivers. While the Arctic sea ice has shown a consistent and significant decline, the Antarctic sea ice has displayed more complex and regionally variable patterns, including a slight increase in extent from 1979 to 2014, followed by a sharp decrease thereafter. However, knowledge on the past changes prior to the satellite era is very limited and, given the high variability in Antarctic sea ice and the influence of both natural and anthropogenic factors, predicting future trends is challenging. The recent decline in sea ice since 2015 has raised questions about whether Antarctic sea ice may now be on a long-term decreasing trend similar to the Arctic, or has reached a new state, though more data and further studies are required to confirm this.

A major issue in the uncertainty is the small thickness of the Antarctic sea ice. If a climate model has a small bias in the net energy flux to the ice, it results in large relative errors in ice thickness changes during the melting and growing seasons. Further, considering ice drift, it has been shown that close to the Antarctic coast the modelled ice motion is more convergent than observed, and near the ice edge the modelled ice is advected faster than observed [103]. Although CMIP6 models show modest improvements in projecting Antarctic sea ice loss compared to CMIP5, uncertainties remain tied to climate sensitivity [104].

The foreseen sea ice decline in the Southern Ocean will have major impacts on the physical climate system both regionally and globally. The further decreases in surface albedo in the Southern Ocean will have increasingly large effect on the planetary albedo. Large turbulent surface fluxes of heat and moisture over new areas of open water will contribute to further warming and moistening of the atmosphere over the Southern Ocean. Simultaneously, these turbulent surface fluxes and the salt fluxes related to new ice formation will drive water mass transformation in the coastal seas regulating the formation of the dense Antarctic Bottom Water (AABW) and the oceanic heat transport under ice shelves [96]. AABW fills a large part (38 %) of the World Ocean [105], and the oceanic heat under ice shelves affects the glacier and freshwater flow rate towards the ocean. Hence, there will be implications for global ocean stratification and meridional overturning circulation [96] and for the global sea level [106]. Reduced AABW formation due to less sea ice can weaken global ocean circulation, with potential impacts on climate patterns worldwide [107].

In addition to the physical climate system, the Antarctic sea ice decline will affect marine ecosystems that rely on stable ice conditions [98]. For example, krill populations, which are essential to the food web, depend on sea ice for breeding and feeding. Effects will probably reach also penguins, seals, and whales [108].

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