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Arctic sea ice and climate change – will the ice disappear in this century?

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A consensus among climate change prediction scenarios using coupled ocean-climate general circulation models (GCMs) is enhanced warming in the Arctic. This suggests that changes in the Arctic sea ice cover may provide early indications of global warming. Observational evidence of substantial changes in the ice cover has been found recently using data from satellites and submarines. Satellite-borne microwave sensor data analyses have established a 3% per decade decrease in the spatial extent of the Arctic ice cover in the past 20 years. Moreover, a 7% per decade decrease in thicker, multi-year (perennial) ice pack has been revealed. This apparent transformation is corroborated by independent data that indicate substantial decreases in the average ice thickness from 3.1 to 1.8 m from the 1950s/1970s to the mid 1990s, averaging about 4 cm per year. It remains uncertain whether these observed changes are manifestations of global warming or are the result of anomalous atmospheric circulation – or both. However, if the recent trends continue, the Arctic sea ice cover could disappear this century, at least in summer, with important consequences for the regional and global ocean–climate system. This article synthesizes recent variability and trends in Arctic sea ice in the perspective of global climate change, and discusses their potential ramifications.

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Climate change and the arctic

The Earth's climate system is presently undergoing an uncontrolled experiment as a result of man's increasing emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases – gases that exert a positive radiative forcing of climate – into the atmosphere, as well as anthropogenic aerosols (microscopic particles) that have a negative radiative forcing. As a net result of these forcings and associated dynamics, changes in global mean temperature are predicted to exceed their natural variability between the decades 1980 and 2010[1]. An assessment of the Intergovernmental Panel on Climate Change (IPCC) concluded cautiously that the balance of observational evidence already suggests a discernable human influence on the global climate[2].

As a complement to observational studies, numerical models are used to better understand climate and climate change including the effect of anthropogenic emissions of greenhouse gases and aerosols. ① The most advanced climate models are coupled oceanic and atmospheric general circulation models (GCMs). These models simulate the climate system based on physical laws describing the dynamics and physics of the ocean and atmosphere, and include representations of land-surface processes and other complex processes including those related to sea ice. Model runs include changes in external forcings such as those from increasing greenhouse gases and aerosols. A consensus from the numerical modelling community is that greenhouse warming will be enhanced in the polar regions, especially the Arctic (Figure 1). Their predicted warming predicted for Arctic is ~3–4°C during the next 50 years[3] with a substantial retreat of the Arctic sea ice cover[4].

② The reasons for enhanced Arctic warming foreseen in models are found in atmosphere–ocean–ice interactions or feedbacks within the climate system[5]. A predominant mechanism is the temperature–ice–albedo feedback, which has a positive or amplifying effect. For example, higher temperatures can reduce the extent of highly-reflective sea ice (or snow), which in turn increases the absorption of energy at the surface, which leads to reduced sea ice, and thus the positive feedback loop perpetuates itself.

3 The predominant feature of the Arctic's physical environment is the presence of a sea ice cover, which is perennial in the central Arctic and at least seasonal in the marginal seas. The sea ice cover is an important component of the climate system, modulating the exchange of heat, moisture and momentum between the ocean and atmosphere, as well as ocean stratification and deepwater formation

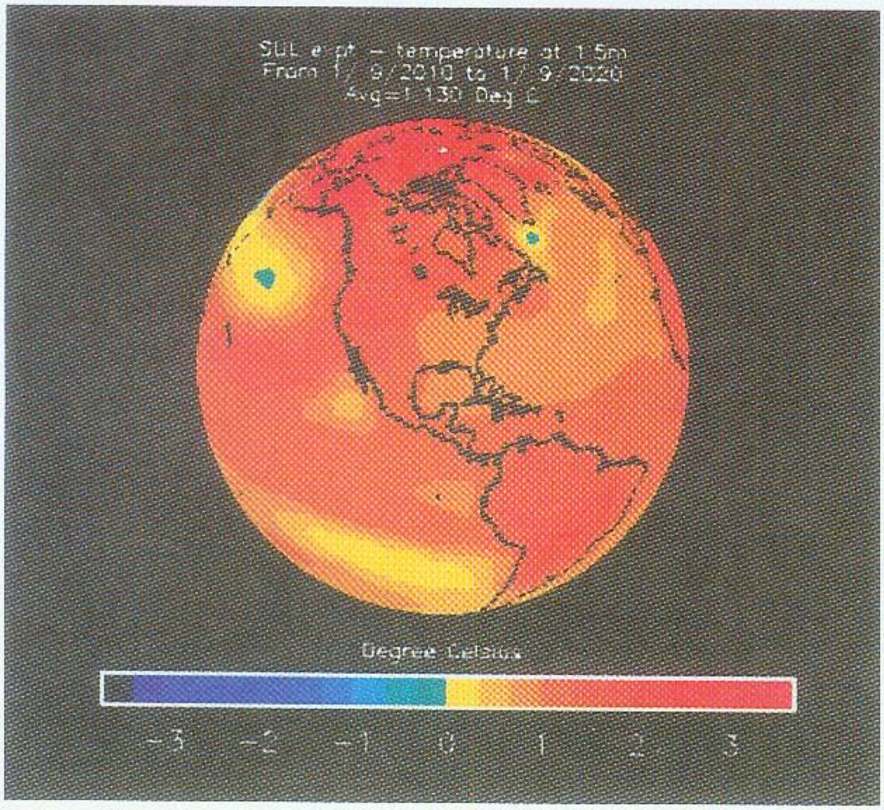

Fig. 1. The geographical distribution of decadal mean surface temperature changes (in degrees centigrade) for the period 2010–2020 with respect to the period 1880 to 1920, as predicted using a coupled ocean–atmosphere general circulation model (GCM). The modelled scenario assumes gradually increasing greenhouse gases (carbon dioxide (CO_2) and others) and sulphate aerosols. (Courtesy, Hadley Centre, UK).

in winter. Sea ice variability can thus both reflect and effect climate change. Sea ice's relatively straightforward (compared to land snow cover) and fast response time (compared to land ice sheets and glaciers) to atmospheric forcings suggests that the observations of the sea ice cover may provide early strong evidence of global greenhouse warming in the Arctic[6]. Moreover, the sea ice cover is a spatially integrated indicator of climate change, in contrast to spatially sparse temperature records available for the interior of the Arctic Ocean.

Arctic sea ice observations

Sea ice data are derived from various sources, each with their particular spatial and temporal sampling and other limitations. Sea ice charts extend back over 100 years in many regions, and gridded datasets of arctic ice extent since 1901 have been produced, albeit with some inherent uncertainties. The most reliable, homogeneous part cover the period since 1953[7] and are derived from operational ice charts including those based at least partly on satellite images since the early 1970s. This dataset provide quantitative information on monthly arctic ice extent, a parameter defined as the area with the ocean – ice boundary. Antarctic sea ice datasets are considerably shorter and less complete.

The most consistent, quantitative means to study the global sea ice cover are satellite passive microwave remote sensor data available without interruption since 1978. Passive microwave sensors measure low-level microwave radiation emitted from the earth's surface and atmosphere. The measured radiance is calibrated to brightness temperature (T_B) and represents a linear function of the emissivity (*i.e.*, radiative efficiency) and the physical temperature (T) of a substance. Even though sea ice has a lower T than open water, it has a much greater microwave emissivity and therefore a higher T_B than open water, for the microwave frequencies used for sea ice retrieval. Algorithms applied to multi-frequency microwave T_B data are used to filter out atmospheric and other effects and then calculate total ice concentration (the percent of ice-covered ocean within an image pixel) (Figure 2), from which total ice extent (the area within the ice–ocean margin), total ice area (the area of ice-covered ocean) and open water area (the difference between extent and area) are derived.

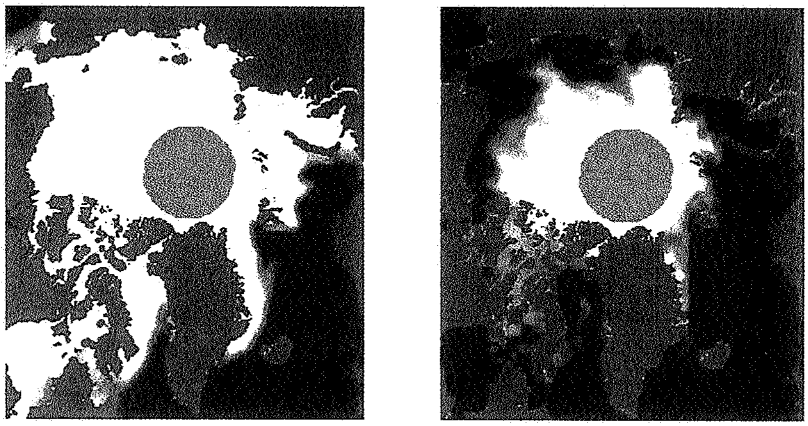

Fig. 2. *Arctic total sea ice concentration in winter (a) and summer (b), as derived from satellite-borne passive microwave sensor data. In these image-maps, ice concentrations (percentage of ice-covered ocean in an image pixel) less than 15% are assigned as zero (open water)).*

As presented later, additional parameters may be retrieved under certain conditions.

Sea ice time series derived from multi-channel passive microwave data are among the longest continuous satellite-derived geophysical records, extending over two decades. The Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) provided data from 1978 to 1987, and the follow-up Special Sensor Microwave Imager (SSM/I) onboard Defense Meteorological Satellite Program (DMSP) satellites has provided data since 1987. The data are optimally resampled into 25 × 25 km grid cells and then issued by the National Snow and Ice Data Center (USA), providing a standard dataset for the research community to analyse sea ice variability and trends.

Arctic sea ice variability and trends

Observation studies of microwave-derived sea ice concentration and derived parameters indicate that variability on time scales of days to weeks and longer is usually organised into geographical patterns that are associated with synoptic-scale pressure systems and larger-scale structures of atmospheric circulation variability. In the context of climate change detection, this high-frequency variability is considered to be essentially background noise, such that climate change analyses based on sea ice data tend to be based on monthly averages. The predominant variability in arctic (or antarctic) sea ice time series is seasonal, with typical late winter (March) maximum ice extent ~15 × 10^6 km^2, compared to a late summer (September) minimum ~5 × 10^6 in the Arctic, though the absolute values may vary from study to study due to operational differences. Figure 3a shows the seasonal cycle in arctic sea ice area, 1978–98. The seasonal variability in the Antarctic (not shown) is even greater, with the late austral summer being nearly ice-free. The seasonal cycle can be readily removed statistically, leaving a series of departures or anomalies from which remaining irregular variability and trends can be determined (Figure 3b).

The first trend analysis based on SMMR data from 1978–87 found a slight negative trend in Arctic sea ice extent[8]. The 0.032 × 10^6 km^2 yr^{-1} decrease (2.4% per decade) was found to be statistically significant, with no significant trend found in the Antarctic. Subsequent data from the SSM/I provided the basis to follow-up on the SMMR-derived trends. An independent analysis of SMMR and SSM/I records taken separately revealed a greater reduction in arctic sea ice area and extent during the SSM/I period. The decreases from 1987 to

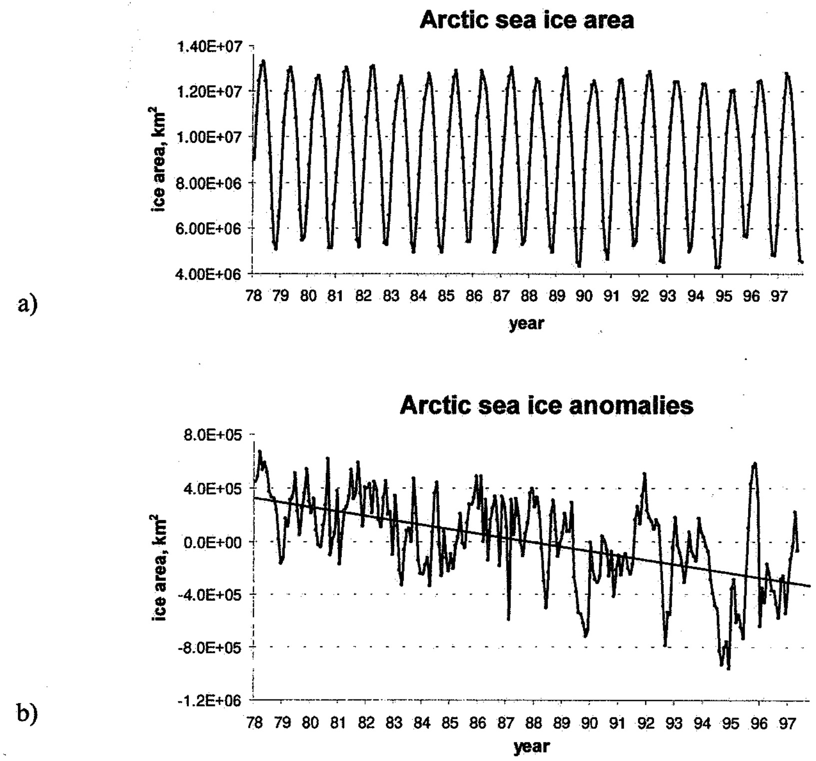

Fig. 3. *Arctic total sea ice area 1978–98 as derived from satellite passive microwave sensor data. Shown are monthly averages (a) and anomalies (b). The linear regression (bottom) indicates a negative trend ~0.03 10^6 km^2 per year, which represents a nearly 6% decrease during the observation period.*

1994 were ~4% per decade compared to ~2.5% per decade from 1978 to 1987, again with no significant trends found in the Antarctic[9]. The Arctic's apparently shrinking sea ice attracted considerable attention in the international climate change community. However, the high degree of interannual variability, coupled with the brevity of the individual time series compelled researchers to produce longer time series and more robust trend estimates.

Since then, merged SMMR-SSM/I time series have been produced and analysed, establishing the trends more firmly. The merging of SMMR and SSM/I involves intercomparison and adjustments (*i.e.*, "intercalibration") based on the 6-week overlap period when both sensors operated. The first published merged SMMR-SSM/I analysis[10] established the trend in Arctic ice area and extent (1978–95) to be about -0.3 × 10^6 km^2 per decade, corresponding to

~3% per decade, with no significant change in the Antarctic. The ~3% per decade decrease in the Arctic ice extent (1978–97) was subsequently corroborated in other analyses[11,12]. The latter also identified the seasonal and regional patterns of trends, while the former confirmed the hemispheric asymmetry seen earlier[9,10]. The antarctic sea ice cover may have even increased slightly (~1.5%)[11], though there is disagreement as to the statistical significance of such a small trend[10,11]. The hemispheric ice covers fluctuate quasi-periodically, with predominant periods between 3 and 5 years, though their variability is apparently not correlated[11]. The cause of this quasi-periodic behaviour may be related to large-scale atmospheric teleconnection patterns such the El Niño Southern Oscillation (ENSO)[13].

The seasonality and forcing mechanisms behind the decreases in arctic ice extent in the 1990s were then analysed using SMMR-SSM/I data (1979–95) together with meteorological data fields[14]. The ice reductions were found to be most pronounced in the Siberian sector in the summer, with record low arctic ice minima in 1990, 1993 and 1995, apparently linked to atmospheric circulation anomalies – in particular, an increase in low pressure systems and associated advection of warm air from the Eurasian landmass in the 1990s. The pronounced summer reductions suggested consequential changes in other aspects (*e.g.*, perennial ice pack) of the ice cover.

Perennial versus seasonal sea ice

Perennial, multi-year ice (*i.e.*, having survived the summer melt) ice is ~3 times thicker than first-year or seasonal ice (~1–2 m), such that changes in their distribution could also both reflect and effect climate change. As mentioned earlier, multi-year (MY) and first-year (FY) ice have different radiative properties, permitting discrimination using multi-channel passive microwave T_B data, during the winter months when their signatures are relatively stable (Figure 4). In summer, the effects of melt ponds and melting snow on the ice confound the signal.

The possibility of monitoring interannual variations in MY ice area was explored earlier using SMMR data[15], but its potential has remained under-realised until recently. In a recent study, 20 years of the SMMR and SSM/I data were used to produce and analyse spatially-integrated time series of MY and FY ice areas in winter, revealing the ice cover's changing composition[16]. The methods used in the analysis were based on the approach used previously for merging SMMR-SSMI sea ice time series[10], with additional methods for robust estimation of MY and FY ice areas. Because the SMMR-

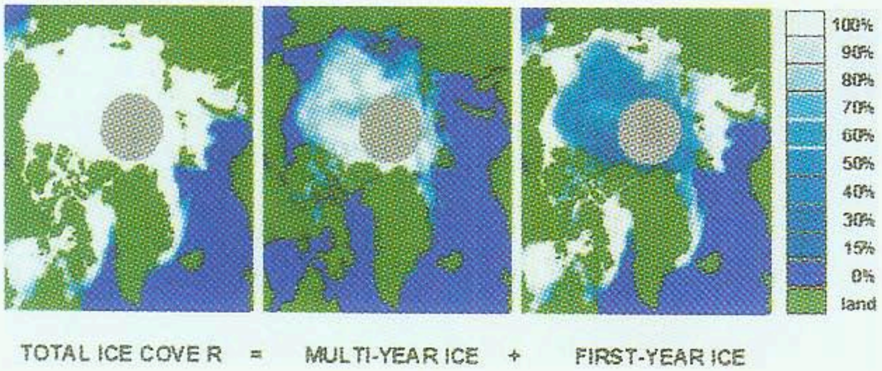

Fig. 4. *Arctic total sea ice cover and its two components, multi-year (MY) and first-year (FY) ice, as derived from satellite passive microwave sensor data in winter. The scale indicates the concentration (percentage) of each ice type in each image pixel.*

SSMI sensor overlap occurred during the boreal summer (*i.e.*, unstable ice signatures), it was unreasonable to directly inter-calibrate the SMMR- and SSMI-derived MY and FY ice areas, as was done for total ice concentration. Instead, the estimates were made by: (i) fine-tuning assumed MY ice emissivities based on arctic field measurements; (ii) fine-tuning the weather filters to reduce false ice signatures off the main ice edge; (iii) analysing spatial and temporal variations in the MY ice distribution for coherence; (iv) comparison with independent field and aerial data; and (v) analysing each summer's minimum ice area in conjunction with the following winter's MY ice area, which should correspond[15]. The last-mentioned procedure (v) confirmed a close correspondence ($r \sim 0.82$), with the winter-averaged MY ice area only 13% less than the summer minimum – substantially closer than the 25–40% obtained previously[15]. The difference is partially explained by the metamorphism of second-year ice into mature MY ice, such that the microwave-derived MY ice area generally increases during the winter – the MY ice area in late winter (March) is only 9% less than the summer minimum. The remaining difference may be largely explained by ice outflow through the Fram Strait (between Greenland and Svalbard) during winter. Therefore, the time series of MY and FY ice areas could reasonably be considered to represent the character of the winter ice cover.

The winter-averaged MY area decreased 0.031 x 10^6 km^2 yr^{-1} (Figure 5) compared with a total ice area decrease of 0.024×10^6 km^2 yr^{-1} averaged over the same 5 months. The difference (0.007×10^6 km^2 yr^{-1}) represents replacement by FY ice, such that the proportion of MY to FY ice changed accordingly. The 0.031×10^6 km^2 yr^{-1}

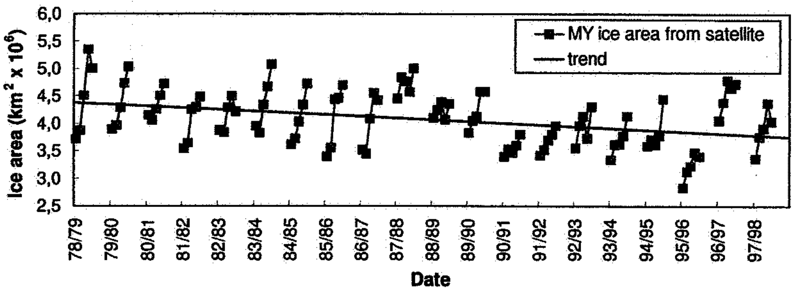

Fig. 5. Arctic multi-year (MY) sea ice area in winter (November–March) as derived from satellite passive microwave sensor data. The linear regression indicates that the MY ice area decreased by ~610,000 km² during the 20-year observation period, which represents an ~14% decrease.

decrease in MY ice area represents a proportionally large (~7% per decade) reduction in the MY ice area 1978–98 (Figure 5), compared with an ~2% per decade decrease in the total ice area in winter[16]. The apparent 14% reduction in MY ice area over two decades is corroborated by other analyses, such as a SMMR-SSM/I data analysis that found an 8% increase (5.3 days) in the length of the sea ice melt season in the Arctic from 1978 to 1996[17]. It is also supported by an analysis of oceanographic data that has revealed changes in Arctic water masses since the 1970s that are reasoned to stem from a substantial (~2 m) melting of perennial MY ice[18].

In order to assess the significance of the observed reductions in MY ice area in terms of the ice cover's mass balance, spatially- and temporally-coincident data on ice thickness are needed. Spatially averaged ice thickness estimates[19,20] from Russian drifting stations have been compared with MY ice area during the common observation period 1978–91 (Figure 6) finding a close correspondence ($r \sim 0.88$) between these independently derived parameters. The strength of the correlation was unexpected – after all, MY ice could become substantially thinner and still count towards the MY ice area. However, the observed relationship with ice thickness suggests that the observed decrease in MY ice area (1978–98) represents a substantial (*i.e.*, mass balance) rather than a peripheral effect.

However, the available data remain inadequate to produce a real climatology of arctic ice thickness[21], and there remain great uncertainties concerning ice thickness trends. For example, the above-mentioned ice thickness estimates indicate a less than 10 cm decrease per decade, substantially less than results from analyses of nuclear submarine data. The submarines carry upward-looking sonar

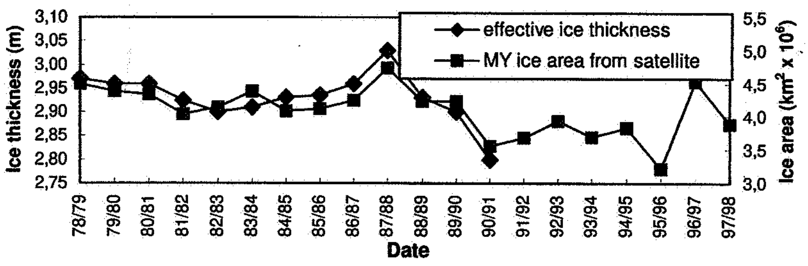

Fig. 6. Arctic Ocean sea ice thickness and multi-year (MY) sea ice area in winter (November–March), as derived from ice surface measurements (1978–91) and satellite passive microwave sensor data (1978–98). The strong correlation (r ~0.88) between the ice parameters during the overlap suggests that observed areal decreases in MY ice area are associated with decreases in ice thickness, rather than representing only peripheral changes.

to measure their distance from the underside of the sea ice cover, permitting estimates of ice draft, and hence, ice thickness. Recently, an analysis of submarine sonar transect data from US submarines from 1958, 1976, 1993, 1996 and 1997 found that between the 1950s/1970s and the 1990s, the mean ice thickness decreased from 3.1 m to 1.8 m[22]. The 1.3-m decrease corresponds to about 15% per decade and is estimated to represent a nearly 40% decrease in ice volume[22]. While this finding is indeed remarkable, the spatially- and temporally-fragmentary nature of the observations underscores the need for integrated datasets of arctic ice thickness, such as those being developed from satellite-borne altimeter data, available without interruption since 1991[23].

Sea ice and climate variability

The balance of observational evidence indicates a sea ice cover in transition, which could eventually lead to a different ice-ocean-atmosphere regime in the Arctic, altering heat and mass exchanges as well as ocean stratification. However, 20 years of microwave satellite data may be inadequate to establish that this is a long-term trend rather than reflecting decadal-scale atmosphere-ocean variability such as ENSO and the North Atlantic Oscillation (NAO)[24]. The NAO is the tendency for simultaneous strengthening or weakening of the Icelandic Low and the Azores High, the two semi-permanent atmospheric pressure centres in the North Atlantic. The NAO is strongest in winter, though it remains the predominant mode of atmospheric circulation in the region year-round. In its positive

mode, it leads to enhanced westerlies across the North Atlantic, associated with positive anomalies in storminess, precipitation and temperature in northern Europe and beyond. Recently, another apparent mode of high-latitude atmospheric variability, the so-called Arctic Oscillation (AO)[25], has been introduced. The AO describes the dominant spatial pattern of variability in mean sea level pressure (SLP) north of 20° N, encompassing the regional NAO. Although its proponents consider it to be a more fundamental structure than the NAO, their temporal correlation in the Atlantic sector is 0.95, such that it may be essentially indistinguishable from the NAO[26].
Interannual variability in the NAO is known to be strongly coupled to fluctuations in arctic sea ice motion[27] and ice export through the Fram Strait[28], as well as regional sea ice extent[29,30]. The NAO winter index has also been found to be lag-correlated with the arctic minimum ice area following summer, and hence the following winter MY ice area ($r = -0.54$), such that the NAO index explains ~25% (r^2) of the MY ice variability[16]. The connection to atmospheric circulation anomalies underscores the need to consistently produce and analyse longer-term sea ice datasets. Indeed, it is possible that should atmospheric circulation anomalies seen in, *e.g.*, NAO and AO indices during recent decades return to "normal", the arctic sea ice cover would probably rebound accordingly. On the other hand, these atmospheric circulation anomalies themselves may be part of global warming. For example, some greenhouse warming modelling analyses indicate increasingly positive states of the NAO and AO. Furthermore, a recent comparison of GCM-simulated sea ice extent and observed sea ice trends concludes that there is less than a 2% chance that the 1978–98 sea ice trends arise from natural variability, and less than 0.1% for 1953–98 sea ice trends[31].

Consequences of a melting sea ice cover

Extrapolating the estimated[22] thinning rate of the ice cover of 4 cm yr^{-1} indicates that the Arctic Ocean could be essentially ice-free in summer in the next 50 years. Present uncertainties about recent and future melting rates notwithstanding, there is a range of potential consequences – some 'negative' and some 'positive' – of a disappearing ice cover that can be hypothesized:

(i) Dramatic reductions in albedo would have significant effects on radiation and energy balances and atmospheric and oceanic circulation in the high- and mid-latitudes, hence altering weather patterns and storm tracks, frequency and intensity

(ii) Exposure of vast areas of the Arctic Ocean with cold open water, which has a high capacity for CO_2 absorption, could become an important sink of atmospheric CO_2, thus mitigating global warming. For example, first-order estimates based on measurements of carbon fluxes in the Greenland Sea[32] and a box model indicate that 0.3–0.6 Pg of carbon could be absorbed each year by an ice-free Arctic Ocean, a 15-30% increase from what the world ocean absorbs presently

(iii) Broad changes in the marine ecosystem (*e.g.*, less plankton in the North Atlantic due to less ice and greater inflow of melt-water[33]) would have a negative impact on arctic and sub-arctic marine biodiversity, though with an increased area for fisheries in previously ice-covered areas, as well as increased offshore and gas activities and marine transportation, including the Northern Sea Route north of Siberia.

(iv) Changes in the pathways and spreading of melt water and in the stratification in the northern North Atlantic Ocean, and the effects of reduced deepwater formation on the global thermo-haline circulation[34] (the so-called "conveyer belt"), which could diminish or otherwise change the Gulf Stream and transatlantic drift stream[35], thereby greatly altering the climate of Europe.

It is therefore of utmost importance that monitoring and research on the Arctic Ocean and surrounding seas be prioritised as one of the "grand challenges" for the international science community. Further systematic monitoring and analysis of sea ice and other high-latitude environmental parameters[36] such as ice sheets, glaciers, snow cover and permafrost, together with oceanographic and atmospheric data as well as modelling simulations, are needed to better understand the patterns, processes and consequences of climate change in the Arctic.

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