Impacts of Climate Change on Arctic Sea Ice

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KEY FACTS

What is already happening?

- The extent and thickness of Arctic sea ice continues to decrease in every month of the year, but especially in late summer to early autumn (July–October).
- Satellite records from 1979 to 2022 show that Arctic sea ice extent at the seasonal minimum in September has reduced on average by almost 79,000 km^2 per year, or around 12% per decade compared to the 1981–2010 mean.
- More than half the observed loss of Arctic sea ice can be directly attributed to warming caused by anthropogenic greenhouse gas emissions.

What could happen in the future?

- It is virtually certain that Arctic sea ice will continue to decline in response to global warming caused by rising atmospheric CO_2 concentrations.
- It is likely that the Arctic will become practically ice-free at the seasonal minimum at least once before 2050, regardless of the future emission scenarios. This loss is not irreversible and Arctic summer sea ice should recover if Arctic temperatures reduce.
- Changes in the timing of sea ice formation and melt are likely to further increase total primary production in the Arctic Ocean. This is likely to cause a mismatch in demand for food and habitat for marine species, with potential impacts on Arctic fisheries.
- It is virtually certain that the Arctic will continue to warm faster than the rest of the globe. The resulting reduction in the equator-to-pole temperature gradient has the potential to affect mid-latitude (UK) climate, including via possible changes in the jet stream.

- These rapid changes in the Arctic have the potential to cause rapid and unexpected changes in the midlatitude North Atlantic via the outflow of fresh, cold, polar water from the Arctic into the subpolar North Atlantic.

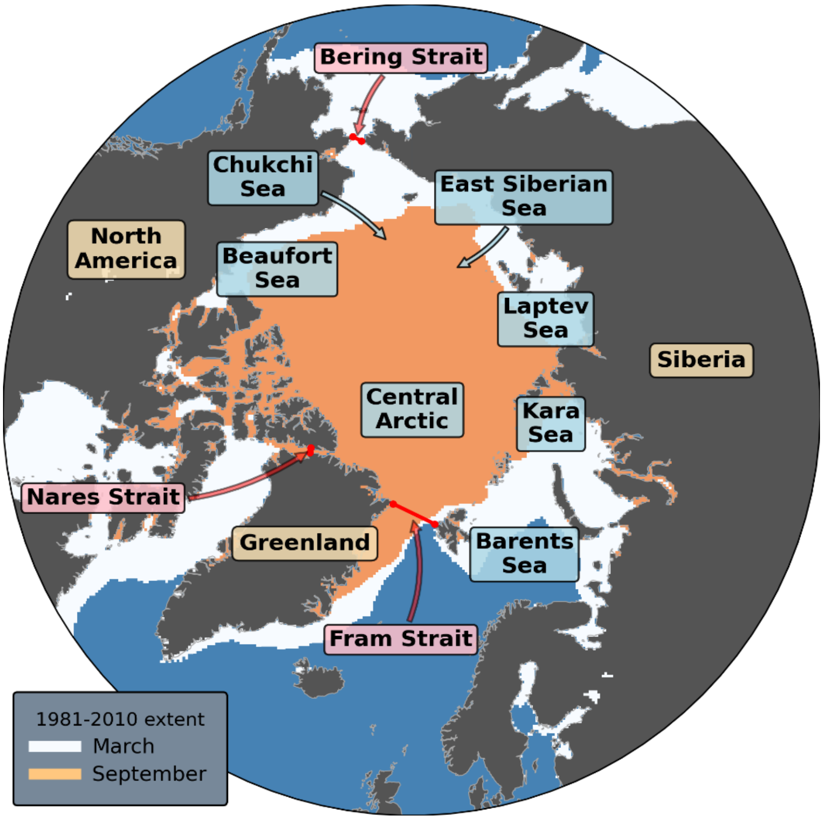


Figure 1: Annotated map of the Arctic illustrating the location of various regional seas, straits, and land masses referred to in this report. The coloured shading shows the 1981–2010 median sea ice extent for March (white) and September (orange) derived from the OSI SAF Climate Data Record (OSI SAF, 2022).

SUPPORTING EVIDENCE

What is already happening?

Arctic sea ice extent decline

Satellite sensors record a downward trend in Arctic sea ice extent for all months (Figure 2; Fox-Kemper *et al.*, 2021). This trend is particularly pronounced in the summer months (June to October) in which ice extent of the most recent five years (2018–2022) has consistently remained below the 1981−2010 inter-decile range. Over the satellite period of 1979 to 2022, the September ice extent has reduced, on average, by almost 79,000 km^2 each year, or around 11.5% per decade when referenced to the long-term (1981–2010) mean September extent of 6.88 million km^2 (OSI SAF, 2020). The various satellite products all agree that Arctic sea ice extent has considerably declined over the last 43 years. However, they all report slightly different values, for example the NSIDC sea ice index reports an average decline of approx. 79,100 km^2 per year over the period 1979–2022, just over 12.3% per decade relative to their 1981–2010 mean of 6.41 million km^2.

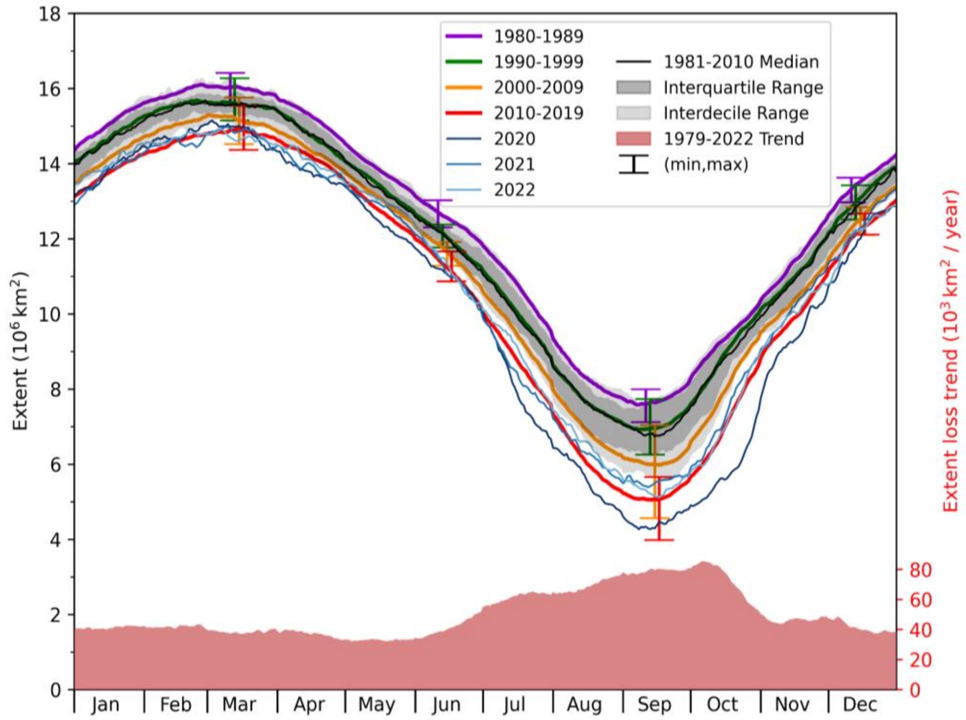


Figure 2: Pan-Arctic sea ice extent for each day of the year from 1980 to 2022. Thick lines represent decadal means for 1980s-2010s with error bars showing minimum and maximum values for selected months (March, June, September, December); individual years 2020–2022 are represented with thin blue lines. Also shown are the 1981–2010 median (thick black line), inter-quartile, and inter-decile ranges (grey shading). The pale red shaded region shows the trend in sea ice extent over the period 1979 to 2022 for each day of the year (right-hand axis). Data are from OSI SAF Sea Ice Index v2.1 (OSI SAF, 2020).

Arctic sea ice is thinning

Not only is the extent of Arctic sea ice changing, but it is also thinning (Lindsay and Schweiger, 2015), and the area of thick multiyear ice that has survived at least one summer has significantly reduced (Kwok, 2018). A synthesis of in-situ and satellite data from 1958–2018 indicates an Arctic-wide thinning of 2 m (or 66% relative to pre-1990) over the past six decades (Kwok, 2018). Confidence in pan-Arctic estimates of winter sea ice thickness has grown since the launch of radar altimeter CryoSat-2 (2010 to present) and laser altimeter ICESat-2 (2019 to present) (Petty *et al*., 2023). Landy *et al*. (2022) have now extended this time-series data to the year-round seasonal cycle by also retrieving pan-Arctic sea ice thickness in the summer. Results show that over this period the thickness trends are insignificant in the central Arctic and could be underestimated by up to a factor two in the Marginal seas (e.g. 62% in the Laptev sea, 81% in the Kara Sea and 102% in the Barents Sea; Mallett *et al*., 2021). This effect is attributed to the underestimated decline of the snow thickness as discussed below.

Decline of Arctic land-fast ice

Land-fast sea ice (or 'fast ice') is motionless sea ice that is held fast by the coastline, the sea floor, or grounded icebergs. Fast ice plays a role in the formation of polynyas and provides hunting grounds and transport links for indigenous communities and megafauna (Meier *et al*., 2014). The total area of Arctic land-fast ice is also in decline. Observations of land-fast ice area derived from ice charts suggest that the total area of winter Arctic land-fast ice declined, on average, by over 12,000 km^2 per year (6.6% per decade) during the period 1976–2007. Reductions are particularly significant in the Laptev and Chukchi Seas, as well as around Svalbard and north of the Canadian Arctic Archipelago (Yu *et al*., 2014). In addition to reduction in the areal extent, IPCC AR6 report thinning of land-fast ice in the Svalbard Arctic border (Fox-Kemper *et al*., 2021).

The loss of ice affects snow cover on sea ice

Snow accumulation at the surface of sea ice has a strong effect on the thermophysical and optical properties of the combined ice and snow system. Snow is a very poor thermal conductor, thereby limiting the rate of sea ice growth, and has a reflectivity considerably higher than bare ice (Perovich and Polashenski, 2012). The deep snow provides a habitat for megafauna, such as ringed seals and polar bears, whereas the depth of the snow regulates how much light penetrates through the sea ice to the ocean, affecting the productivity of ice-algae and under-ice phytoplankton blooms. It has been observed that the mean thickness of snow accumulating on sea ice has declined from approximately 35 cm to 22 cm in the western Arctic and from 33 cm to 15 cm in the Beaufort and Chukchi Seas since the mid-1900s (Webster *et al*., 2018). This thinner snow cover is primarily caused by the combination of a loss of multiyear ice and later freeze-up dates that lead to lower total end-of-winter snow accumulation. Although snowfall is theoretically one of the principal controls of snow accumulation on Arctic sea ice (Webster *et al*., 2018), snowfall changes are likely small, with reanalysis trends generally negative or close to zero (Reader and Steiner, 2022). Negative snowfall trends are attributed to an increase in the fraction of precipitation falling as rain, rather than a decrease in total precipitation, for which trends are generally positive (Reader and Steiner, 2022).

Sea ice drifting faster

Analysis of more than three decades of pan-Arctic sea ice drift data from sea ice buoys and satellite sensors reveal an overall increase in strength of ocean currents in the Beaufort Gyre and Transpolar Drift, particularly over the last decade (Kwok *et al*., 2013; Olason and Notz, 2014; Krumpen *et al*., 2021). This strong positive trend in ice drift speeds, of around 20% per decade, can be partly explained by multiyear ice loss and the increase in areas with relatively low ice concentration (Olason and Notz, 2014). However, during the MOSAiC expedition (Krumpen *et al*., 2021) an observed drift speed 20% above the climatological mean was attributed to an increase in storms and low-pressure systems driving intensification of the Transpolar Drift.

Increased ice export

The passage between Greenland and Svalbard (Norway), known as 'Fram Strait', is the area where most of the sea ice is exported from the Arctic. Annual sea ice volume export through Fram Strait has increased since 1979 by 6% per decade, and by 11% per decade during spring and summer (Smedsrud *et al*., 2017). At the same time, collapse of ice-archways in the Nares Strait (Moore *et al*., 2021), and increased multi-year-ice losses in the Beaufort Sea (Babb *et al*., 2022) have resulted in new export pathways for the older ice in the Arctic.

Accounting for changes in Arctic sea ice

Research suggests that more than half of the observed Arctic sea ice extent decline can be attributable to anthropogenic greenhouse gas emissions and the resulting increase in global mean surface-air temperatures (IPCC, 2021; Eyring *et al*., 2021). Several studies have shown that the decline in Arctic sea ice extent is directly linked to atmospheric CO_2 concentration (Notz and Stroeve, 2016) and global temperature (Olonscheck *et al*., 2019). Importantly, if global temperatures were to level out, sea ice extent would stabilise in equilibrium with the forcing (Ridley and Blockley, 2018).

Other primary causes for the changes in the Arctic sea ice

Aside from CO_2-induced warming of the atmosphere, much of the melting of sea ice can be attributed to in-situ ocean warming caused by the increased solar absorption (Kashiwase *et al*., 2017). The decline in surface albedo induced by longer sea ice melting seasons and lower ice concentration increases solar heat input into the Arctic ice-ocean system. This warm upper ocean can cause the ice to melt from below at a rate of up to 0.11 m per day (Perovich *et al*., 2008), significantly contributing to the observed sea ice loss especially in the western Arctic (Timmermans *et al*., 2018).

In the Eurasian Arctic, the intrusion of warm Atlantic inflow is the primary cause for the decline of sea ice extent, particularly in the Barents Sea where the majority of winter sea ice loss has occurred (Polyakov *et al*., 2017). Specifically, an increased heat content of warm Atlantic-origin water leads to a weakening of the halocline, which is the barrier separating an upper layer of cold fresh Arctic water from a lower layer of warmer, more saline Atlantic water (Polyakov *et al*., 2020). The weakening of the halocline has led to a reduction in stratification and increased vertical mixing, causing warm, saline Atlantic waters to reach the sea ice and melt it from beneath (Polyakov *et al*., 2017).

Wider implications of declining Arctic sea ice

Marginal Ice Zone is expanding with declining sea ice

One of the biggest impacts of declining and thinning Arctic sea ice is the relative expansion, i.e. increase in the relative fraction, of the Marginal Ice Zone (MIZ) in summer. The MIZ is typically defined as a dynamic area with small ice floes and low ice concentration (15–80%) (Strong *et al*., 2017). This widening of the summer MIZ has been estimated at 39% for the period 1979–2011 from the satellite data (Strong and Rigor, 2013); the corresponding relative summer MIZ fraction has also increased by 50% over the satellite era (1979-2017), as derived from the various observational data sets and models (Rolph *et al*., 2020). The MIZ relative fraction is projected to continue increasing in the future, with MIZ becoming the dominant sea ice regime in the Arctic after the 2050s (Aksenov *et al*., 2017). Transitioning from pack-ice to MIZ will increase light penetration and increase air-sea gas exchange, facilitating primary production, nutrient fluxes to euphotic zone, and carbon exchange across the air–sea interface (Aksenov *et al*., 2017; Rolph *et al*., 2020).

Declining sea ice accelerates Arctic coastal erosion and collapse

Arctic coastal erosion poses a threat to infrastructure, coastal settlements, and the wider marine environment. Arctic coastal erosion rates are an order of magnitude higher than those in the rest of the world and have been increasing for the last few decades, reaching 25–50 m per year for the hotspots in Siberia and Alaska (Terhaar *et al*., 2021; Nielsen *et al*., 2022). The reduction of the compact sea ice in the Arctic shelf seas allows higher waves to propagate towards the shore (Hošeková *et al*., 2021), causing coastal erosion. The Siberian coastline is presently transitioning from a lower to a higher coastal erosion regime because of the regional sea ice decline. The observed coastal retreat already has reached 400–1100 m over the last six decades in hot spots in the Beaufort and Laptev seas (Grigoriev *et al*., 2019). The currently observed erosion and coastal sediment build-up are increasing in the hotspots in Alaska and Siberia, but the erosion still dominates over build-up (Philipp *et al*., 2022).

Declining sea ice affects primary production and marine wildlife

The loss of sea ice in the Arctic is driving a 30–60% increase in primary production that is presently sustained by intensifying inflow of nutrients into the ocean (Lewis *et al*., 2020). This increase is largely attributed to the growth of open-ocean phytoplankton, but a thinning snow and ice cover is also supporting significant under-ice phytoplankton blooms and increasing growth of sea ice algae (Lannuzel *et al*., 2020). For example, modelling exercises have suggested that changing sea ice conditions permit sub-ice phytoplankton blooms in 30% of the ice-covered Arctic Ocean, where 20 years ago these blooms may have been uncommon (Horvat *et al*., 2017). The diversity and composition of primary producers in the Arctic is also changing, with increasing abundance of more boreal species in some shelf waters and losses of biodiversity in the most threatened habitats, like sea ice. Such shifts in the type of algae comprising blooms are an important consideration, as they can affect bloom productivity (Campbell *et al*., 2017), food quality (i.e. lipid composition), and the potential for sequestration of carbon from the atmosphere through connectivity to cryopelagic-benthic coupling (Honjo *et al*., 2010). Furthermore, the timing of phytoplankton and ice algal blooms is shifting in response to physical changes occurring to the ice-covered ocean, and this could have far-reaching consequences for the aquatic grazers that have naturally timed their reproduction to feed on them (e.g. Søreide *et al*., 2010; Brown and Belt, 2012). As marine animals rely on ice-derived carbon throughout all seasons of the year (Brown *et al*., 2018), declining sea ice would affect marine wildlife more significantly than recently believed.

Declining sea ice affects the transport of nutrients and pollutants

Sea ice plays an important role as a carrier of nutrients, sediments, and biological materials (Krumpen *et al*., 2019). Sea ice also provides a medium for the transport of pollutants; concentrations of microplastics in Arctic Sea ice have been shown to be considerably higher than those found in even the most polluted waters (Obbard *et al*., 2014). The majority of ice-rafted matter is incorporated into newly formed sea ice on the shallow Siberian shelves. The Transpolar Drift therefore plays a key role in the transport of this material within the Arctic, from the Siberian shelves towards the Fram Strait, and eventual export to lower latitudes (Krumpen *et al*., 2019). Despite the observed increase in sea ice drift speed, the long-range transport of ice-rafted materials by sea ice is in decline, linked with the reduction in multi-year ice. The reduced survival rate of sea ice exported from the Siberian shelves means that less ice formed in shallow water areas (<30 m) will reach Fram Strait (a reduction of 17% per decade over 1998–2017). Instead, more ice-rafted material is released in the northern Laptev Sea and central Arctic Ocean, affecting ecological processes and increasing accumulation of sediments and contaminates, with consequences for primary production, and the biodiversity in the Arctic Ocean (Krumpen *et al*., 2019).

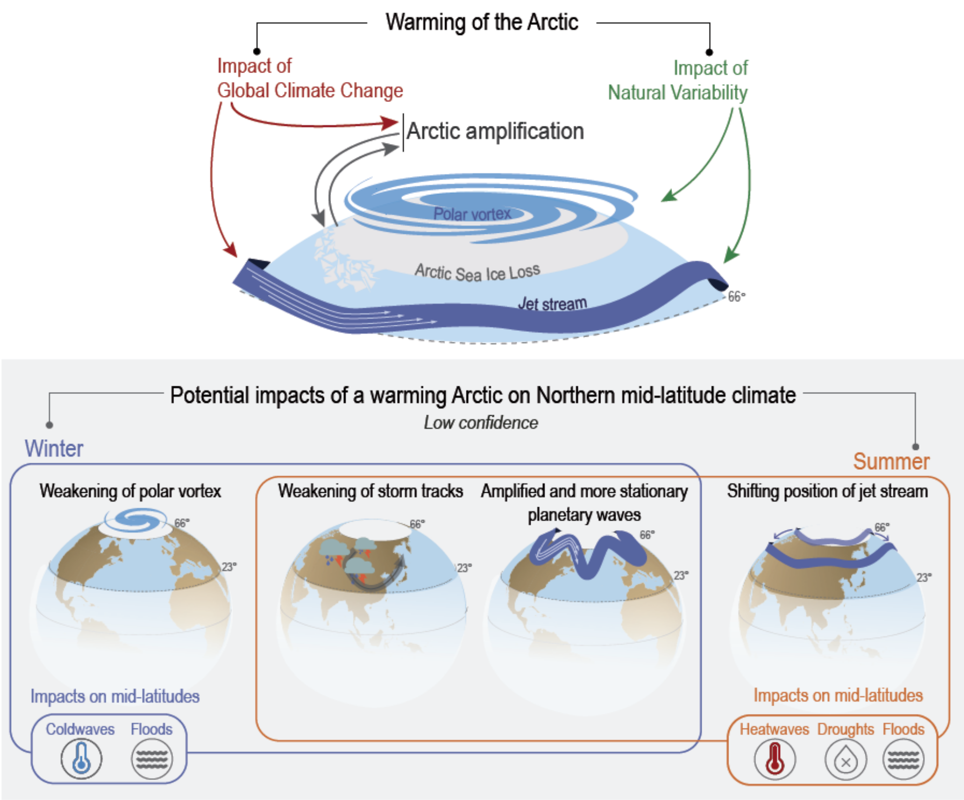


Figure 3: Potential influences of recent and future Arctic warming on midlatitude climate and variability. Mechanisms are different in winter and summer with different associated influences on midlatitudes. The mechanisms involve changes in the polar vortex, storm tracks, planetary waves and jet stream (from Doblas-Reyes et al., 2021, Cross-Chapter Box 10.1).

Declining sea ice potentially affects remote weather and climate

The most immediate effect of sea ice loss is to enhance warming in the Arctic (Screen, 2021). However, evidence suggests the effects of sea ice loss could be felt well beyond the Arctic Circle – possibly including north-west Europe (Barnes and Screen, 2015). As the Arctic warms much faster than lower latitudes, the temperature difference between these regions is reduced. This could cause the jet stream, which exists largely because of the equator-to-pole temperature difference, to slow down and follow a wavier path (Figure 3). Although scientists are reasonably confident that Arctic sea ice loss could affect weather and climate in north-west Europe, the size of this effect is unknown (e.g. Cohen *et al.*, 2020). It is unclear how much of the observed changes in the jet stream and polar vortex are caused by climate change or natural climate variability. Climate model experiments tend to suggest a modest effect of sea ice loss in the midlatitudes, which is small compared to natural variability (Smith *et al.*, 2022). However, even a weak effect could still be important in the future if sea ice loss continues apace. Also, climate models are imperfect, and some studies suggest that the real effects may be larger than models suggest (Smith *et al*., 2022). Essentially, scientists' current understanding of how ongoing Arctic changes impact global weather patterns over a range of timescales from seasons to centuries is imprecise. This has led the Intergovernmental Panel on Climate Change (IPCC) to report only low confidence in the nature of the connections between Arctic sea ice loss and midlatitude weather (Doblas-Reyes *et al*., 2021).

As well as changes to the latitudinal temperature gradient, the outflow of fresh, cold polar water from the Arctic into the subpolar North Atlantic can influence the large-scale ocean and atmospheric circulation (Zhang and Vallis, 2006). It has been suggested that North Atlantic salinity anomalies originate as increased ice and freshwater outflows from the Arctic (Belkin *et al*., 1998; Haak *et al*., 2003; Proshutinsky *et al*., 2015), modulating the decadal hydrographic variability in the subpolar region (Yashayaev, 2007). The resulting cold anomalies in the subpolar North Atlantic have far-reaching implications for the large-scale weather and climate (Mecking *et al*., 2019; Oltmanns *et al*., 2020).

What could happen in the future?

Projection of an ice-free Arctic in climate models

The climate projections used for the IPCC AR6, and many other studies, suggest that the present trends in sea ice area/extent, thickness, snow cover, drift, and MIZ will continue and accelerate (SIMIP, 2020; Fox-Kemper *et al*., 2021). With this continuing decline in sea ice area, the Arctic is likely to be 'practically ice-free' (i.e. extent below 1 million km^2) in September at least once before 2050 under all considered emissions scenarios. However, the future scenarios of greenhouse gas emissions do still play an important role because Arctic sea ice area is related directly to CO_2 concentration and associated global warming (Figure 4a,b). Thus, for projected warming of 1.5–2 °C above pre-industrial levels, September would only be ice-free in some years, whilst at 3°C warming, the Arctic would be practically ice-free in September in most years (Figure 4e). Furthermore, climate models project longer ice-free periods at higher warming levels. This means that for very high warming levels, e.g. following the SSP5-8.5 shared socioeconomic pathway, several climate models project that winter sea ice will start to decline rapidly towards the end of the 21st Century (Figure 4c). Furthermore, there are no identified tipping points associated with Arctic summer sea ice, and so September Arctic sea ice should recover if warming were reversed.

Other key projected changes

The kilometre-scale coastal retreat, observed since the 1960s near several settlements in Alaska, Canadian Northern Territories, and Siberia, is projected to continue (Grigoriev *et al*., 2019; AMAP, 2021). This, along with the mean projected pan-Arctic coastal erosion of ~200 m by 2100 (Nielsen *et al*., 2022), poses a serious socio-economic problem for local populations, but also more widely raising safety and communication concerns (Clare *et al*., 2022; State of the Cryosphere Report, 2022), and an increase of carbon, nutrients and sediments into the Nordic Seas and the North Atlantic, affecting benthic and pelagic ecosystems (Bacon *et al*., 2022). At present, coastal erosion carbon flux is about a third of the Arctic total river source (Terhaar *et* *al*., 2021), estimated from the Arctic Coastal Dynamics climatology (Lantuit *et al*., 2012). Since the climatological mean erosion rates are potentially lower than the present-day rates (Irrgang *et al*., 2022), the current carbon flux can be much higher, with nitrogen and phosphorus fluxes from erosion being already larger than river fluxes (Terhaar *et al*., 2021). The projected Arctic-averaged retreat injects more than 3 Pg carbon into the ocean by the end of the century. Changes to sea ice cover in the Arctic are shifting the base of primary production, which supports the marine food-web from fish to large mammals, towards an increasing dominance of phytoplankton over ice algae. This represents a change in the type and likely the nutritional quality of algae comprising blooms in the Arctic, which has uncertain consequences for the health of marine life.

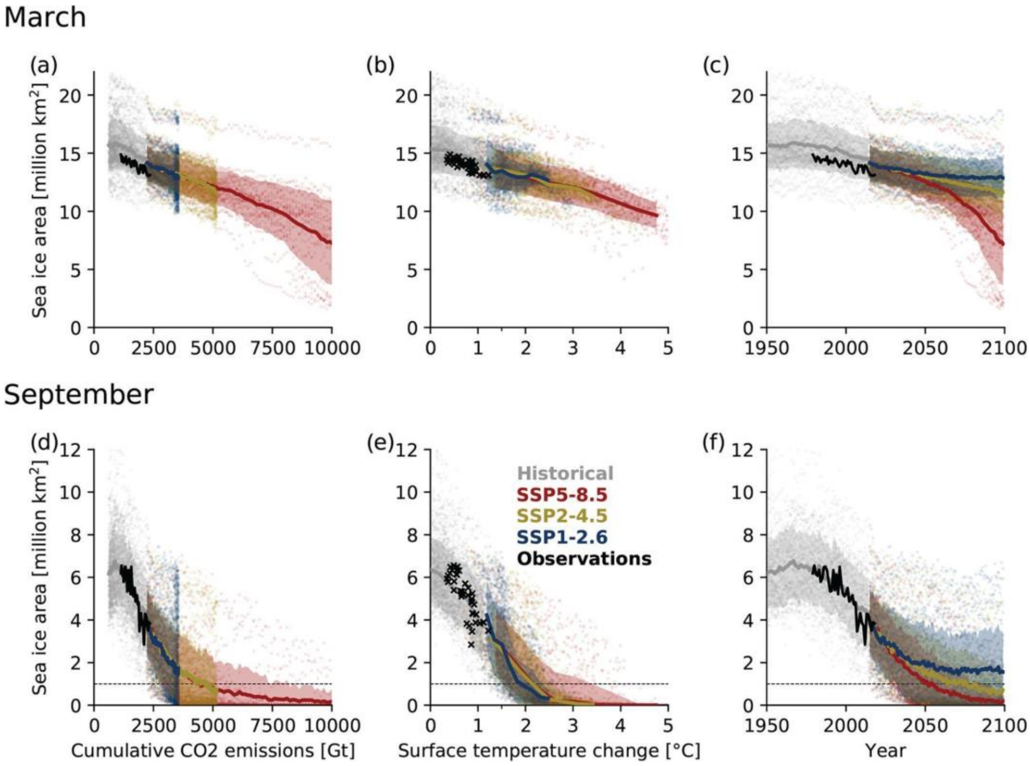
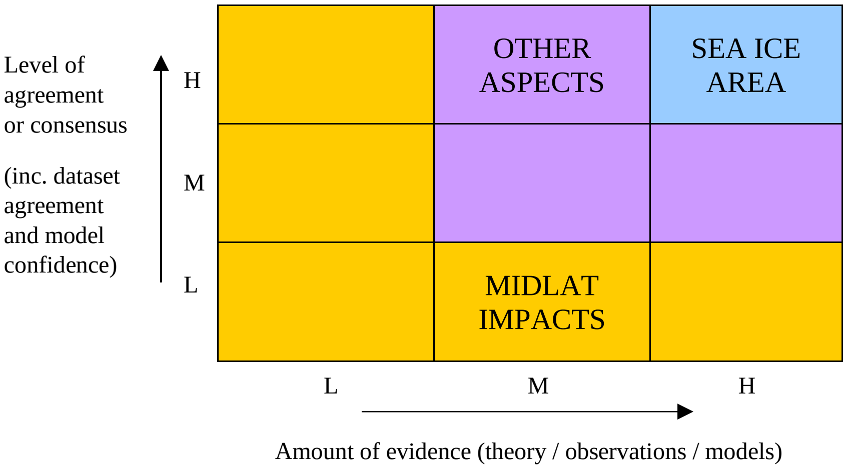


Figure 4: Evolution of Arctic sea ice area over the historical period and three CMIP6 scenario projections in (a–c) March and (d–f) September. Sea ice area is plotted as a function of (a,d) cumulative anthropogenic CO_2 emissions, (b, e) global annual mean surface temperature anomaly, and (c, f) time using 1 ensemble member for each available CMIP6 model. Thick lines denote the multi-model ensemble mean with one standard deviation shading. Faint dots denote the first ensemble member of each model, and thick black lines and crosses denote observations. (from SIMIP, 2020, fig. 2 therein).

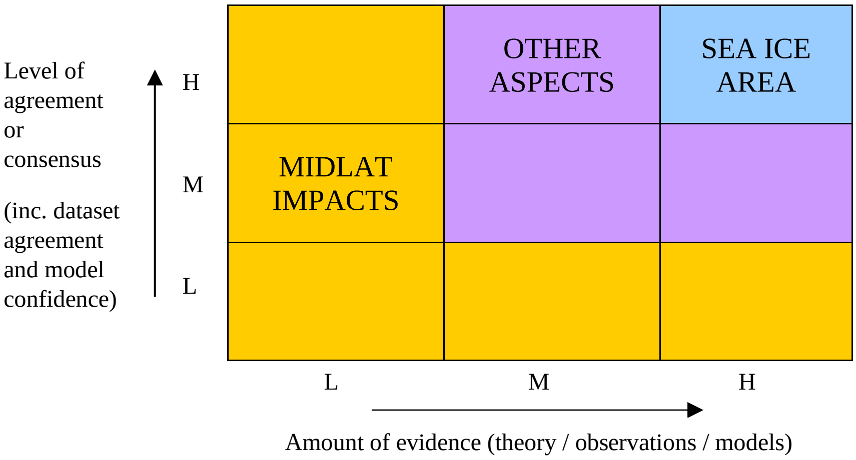
CONFIDENCE ASSESSMENT

What is already happening?



It is beyond question that the Arctic is warming, and that Arctic sea ice extent is declining. Both observations and models provide strong evidence that considerable changes are happening in the Arctic climate system. Therefore, we judge the confidence assessment as 'High-High' for what is currently happening to the areal extent of Arctic sea ice (SEA ICE AREA). However, our understanding of the Arctic processes is not yet complete; we require more accurate observational data such as pan-Arctic snow and sea ice thickness data throughout the year, shortcomings that are well known across the international community. New observational datasets generated from recent, and upcoming Arctic field campaigns such as MOSAiC (https://www.mosaic-expedition.org), and from forthcoming satellite missions (e.g. CRISTAL, CIMR, ROSE-L) will help to increase our understanding of Arctic processes further. However, a key challenge for the community will be the establishment and maintenance of sustained long-term observing systems, whose lack of financing is hindering our understanding of the Arctic climate system. These factors mean that the confidence assessment for the other aspects of Arctic sea ice change is lower than that for areal extent loss. We therefore judge the confidence for other aspects of Arctic sea ice discussed here (i.e. thickness, velocity, snow, coastal erosion, ecosystems) to be 'Medium-High' (OTHER ASPECTS). Furthermore, there is a need for more evidence regarding the midlatitude impacts – in some cases related to the theory of physical understanding, and other cases because of the lack of robust observed responses when compared with substantial internal variability. We judge the confidence assessment as 'Medium-Low' for what is currently happening to midlatitude impacts of Arctic sea ice decline (MIDLAT IMPACTS).

What could happen in the future?



Although climate model physics and the level of agreement among ensembles have been improved, the ‘absolute’ accuracy of climate model projections is difficult to measure owing to internal variability and emission scenario uncertainty (Notz, 2015; Hawkins and Sutton, 2009). However, all climate models agree on the downward trend in sea ice extent continuing for the foreseeable future unless, and until, the global temperature stabilises. On that basis, we assess that the level of agreement that there will be continued loss of Arctic sea ice area, resulting in a seasonally ice-free Arctic, with continuing emissions is high. We therefore assign a confidence assessment of ‘High-High’ for future decline of Arctic sea ice areal extent (SEA ICE AREA). However, the projected rate of decline, eventual ice-free Arctic date, and how specific parameters will change still contains considerable uncertainty (Jahn *et al.*, 2016; Notz, 2015). Additionally, climate models collectively underestimate the loss of sea ice per degree of global warming (SIMIP, 2020), and exhibit considerable spread in the regional representation of sea ice (Watts *et al.*, 2021). Building on our present time-series of data, as well as integrating new observations with expected improvements in model physics, resolution and coupling will further increase our understanding of the Arctic climate system today, and how it may change in the future. We therefore judge that the confidence assessment for future changes to other aspects of the Arctic sea ice discussed here (i.e. ice-free Arctic date, thickness, snow cover, MIZ expansion, coastal erosion, ecosystems) to be ‘Medium-High’ (OTHER ASPECTS). Finally, we judge the confidence assessment as ‘Low-Medium’ midlatitude impacts of Arctic sea ice decline in the future (MIDLAT IMPACTS). Although the higher signal-to-noise ratio arising from the larger response in future model projections gives us increased confidence in the level of agreement between models (Smith *et al.*, 2022), in the absence of observations the amount of evidence is lower.

KEY CHALLENGES AND EMERGING ISSUES

- There is evidence that Arctic sea ice loss could affect weather and climate in north-west Europe, however knowledge of the nature and size of these effects are imprecise. A better understanding is required of the involved mechanisms, their pathways to lower latitudes, and their fidelity in models.
- Assess risks associated with Arctic shipping and offshore operations (e.g. contaminant spills; damage to ships and offshore structures caused by waves, sea ice floes, and icing spray), and land-based infrastructure (e.g. coastal erosion and permafrost decay).
- Comprehensive assessments of ocean biogeochemistry for the ecosystem-based management of rapidly changing Arctic marine systems, including monitoring and knowledge building upon the following areas: life form responses across trophic levels (from microbial life to marine mammals); food security for Indigenous peoples; the impact of increasing terrigenous inputs (inc. rapid carbon discharge and associated changes in nutrients or contaminants).

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