# Impacts of climate change on Arctic sea ice

B. Hwang[1], Y. Aksenov[2], E. Blockley[3], M. Tsamados[4], T. Brown[5], J. Landy[6], D. Stevens[7], J. Wilkinson[8]

[1] *University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK*
[2] *National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK*
[3] *Met Office, FitzRoy Road, Exeter, EX1 3PB, UK*
[4] *Centre for Polar Observation and Modelling, Earth Sciences, University College London, London, WC1E 6BS, UK*
[5] *Scottish Association for Marine Science, Oban, PA37 1QA, UK*
[6] *Bristol Glaciology Centre, University of Bristol, Bristol, BS8 1SS, UK*
[7] *Centre for Ocean and Atmospheric Sciences, School of Mathematics, University of East Anglia, Norwich, NR4 7TJ, UK*
[8] *British Antarctic Survey, Cambridge, CB3 0ET, UK*

**EXECUTIVE SUMMARY**

Satellite measurements continue to reveal reductions in the extent and thickness of Arctic sea ice. Research suggests that at least half of the observed decline of ice extent can be linked directly to anthropogenic greenhouse gas emissions and the resulting increase in global mean surface air temperature. As perennial sea ice has been progressively replaced by seasonal ice cover, we have observed changes to the marine ecosystem, ocean properties, atmospheric circulation, and evidence of Arctic links to extreme weather events at lower latitudes. Under the RCP8.5 future emission scenario, it is very likely that we will see a seasonally ice-free Arctic before 2050. Crucially, if we comply with the terms of the Paris Agreement and limit global average temperatures to below 2.0°C above pre-industrial levels, the likelihood of a seasonally ice-free Arctic will be greatly reduced. Furthermore, if we limit warming to only 1.5°C above pre-industrial levels, then there is a high chance that the Arctic will not become ice free in summer. A warmer Arctic will increase coastal erosion, permafrost thawing and marine pollutants. The future of Arctic marine ecosystem and the sustainability of the fishing industry will be more uncertain due to changing ocean circulation, nutrient flow and light availability.

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## 1. WHAT IS ALREADY HAPPENING?

### Arctic sea ice extent continues to decline

Satellite sensors continue to record a downward trend in Arctic ice extent for all months (Figure 1). This trend is particularly pronounced in the Arctic summer months (May to September) in which ice extent of the most recent five years (2014 to 2018) has consistently remained below the 1981–2010 interdecile range (Figure 2). Over the satellite period of 1979 to 2017, the September ice extent has reduced, on average, by around 83,000 km$^2$ each year, or approximately 13.0% per decade as referenced to the mean September extent for 1981–2010 (Serreze and Meier, 2018). This equates to an area of sea ice larger than the size of Scotland being lost every year. However, the loss of ice is not uniform across the Arctic Ocean. For example, the largest declines of summer ice extent have occurred in the East Siberian, Chukchi and Laptev / Kara Seas (Figure 3), whilst the largest decline in mid-winter ice extent was observed in the Barents Sea (Onarheim *et al*., 2018).

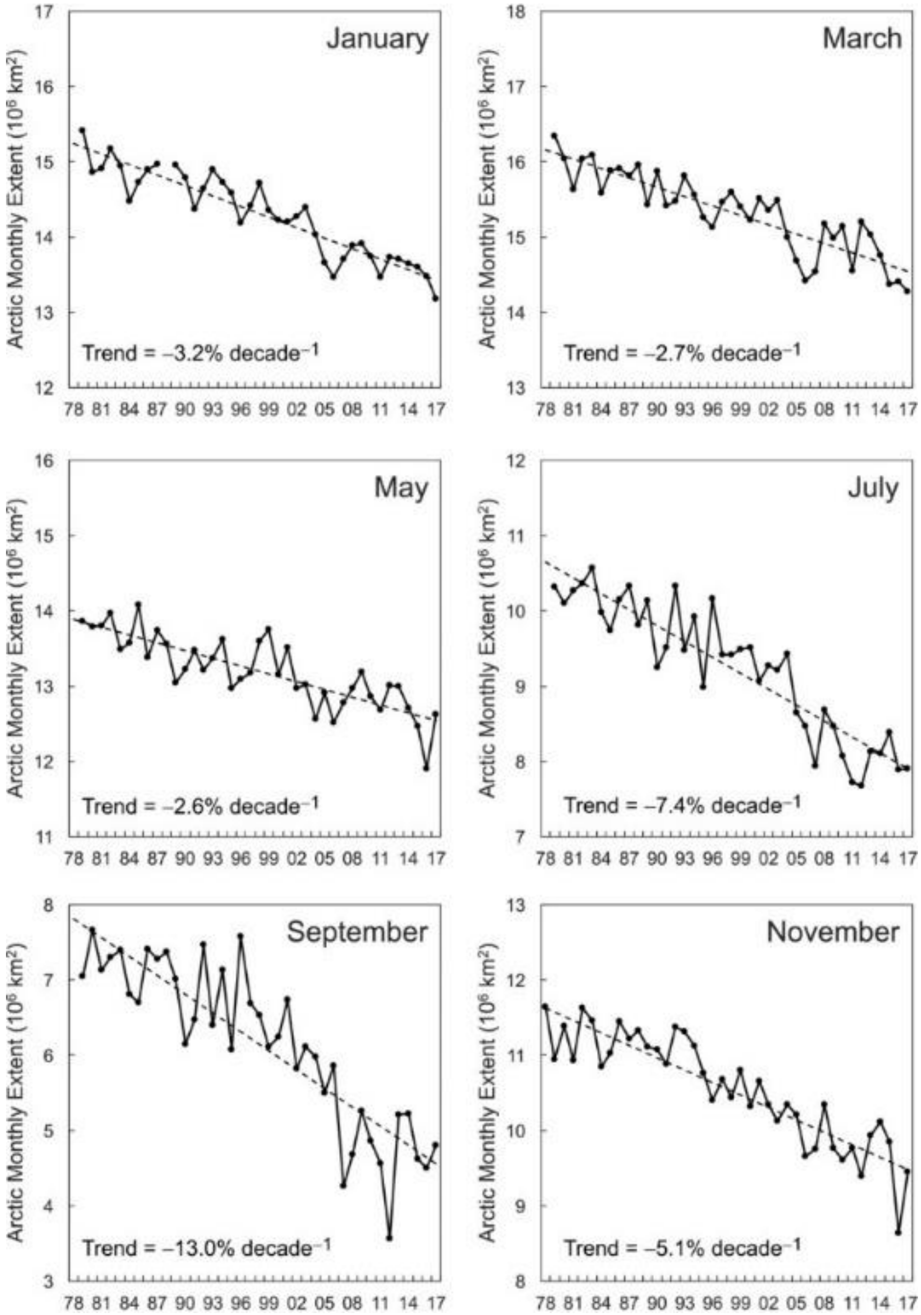



*Figure 1: Time–series and linear trends in Arctic sea ice extent for alternate months, based on satellite passive microwave record over the period of 1979–2017. (From Serreze and Meier, 2018.)*

## Arctic sea ice is thinning

It is not only the extent of Arctic sea ice that is changing, 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). Currently, we do not have the capability to measure sea-ice thickness directly from satellite sensors, however we can infer its thickness from space during winter (e.g. Cryosat-2 radar altimetry) by measuring the height of the ice above the sea surface and converting this into a thickness (Laxon *et al*., 2013). Obtaining reliable ice thickness data in late spring and summer months still remains a challenge, because melt ponds forming at the sea-ice surface provide similar radar reflections to gaps (leads) in the ice pack, and we need to be able to differentiate ice from ocean to measure thickness. The latest synthesis of in-situ and satellite data indicates an Arctic-wide thinning of 2 m (66%) over the past six decades, from an average Central Arctic end-of-summer ice thickness of around 2.8 ± 0.5 m in the 1970s to 1.5 ± 0.1 m in the 2010s (Kwok, 2018). Steep declines in ice thickness measured through the 1990s and 2000s have levelled off recently, with mean Central Arctic mid-winter ice thickness settling around 2 m since 2008. Over the 15-year satellite observation (2003–2018), the total mid-winter sea-ice volume has declined by 2900 km$^3$ per decade while end-of-summer ice volume has declined by 5100 km$^3$ per decade (Kwok, 2018). The enhanced volume loss following summer melting is attributed to steeply declining trends in September–October sea ice extent and progressive replacement of thick multi-year ice by thinner first-year ice (Kwok, 2018). The loss of volume of multi-year ice each summer has contributed significantly to the 5000 km$^3$ additional freshwater accumulated in the Beaufort Gyre since the 1990s (Wang *et al*., 2018).

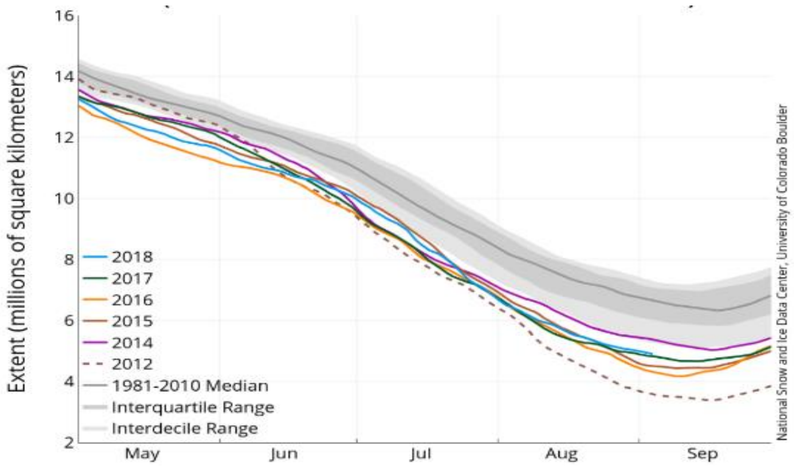



*Figure 2: The graph above shows Arctic sea ice extent (area of ocean with at least 15% sea ice) as of September, 4, 2018, along with daily ice extent data for four previous years and 2012, the year with record low minimum extent. 2018 is shown in blue, 2017 in green, 2016 in orange, 2015 in brown, 2014 in purple, and 2012 in dotted brown. The 1981 to 2010 median is in dark grey. The grey areas around the median line show the interquartile and interdecile ranges of the data. (From NSIDC, 2018.)*

## 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 ice underneath. Snow is a very poor conductor, thereby limiting the rate of sea ice growth, and has a reflectivity up to 50% 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 to 22 cm in the western Arctic and 33 to 15 cm in the Beaufort and Chukchi Seas since the mid-1900s (Webster *et al*., 2014). 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. Monitoring snow thickness on a pan-Arctic scale is particularly challenging, but recent efforts to retrieve snow properties from airborne (Kwok *et al*., 2017) and satellite remote sensing (Lawrence *et al*., 2018; Guerreiro *et al*., 2016; Maaß *et al*., 2013) are showing some promise. Large uncertainties remain in regions poorly sampled by airborne systems, especially over the Eurasian sector and outside of the spring season. Snow thickness from re-analysis products and climate models can differ by a factor of 3 (Chevallier *et al*., 2016). As such, snow on sea ice remains one of the key unconstrained components of the Arctic system in estimating sea ice thickness from satellite altimetry, despite its important role in regulating ice growth (through its strong insulating property), limiting light penetration to the ocean and as a habitat for Arctic animals.

## Sea ice drifting faster

Analysis of almost forty years of pan-Arctic sea ice drift data from satellite sensors reveal an overall increase in strength of ocean currents in the Beaufort Gyre and Transpolar Drift (Figure 3), particularly over the last decade (Kwok *et al*., 2013). This strong positive trend in ice drift speeds (around 20% per decade) cannot be explained by the much weaker trend in wind speeds, but instead by the strong trend in areas of multiyear ice loss and with relatively low ice concentration (Olason and Notz, 2014).

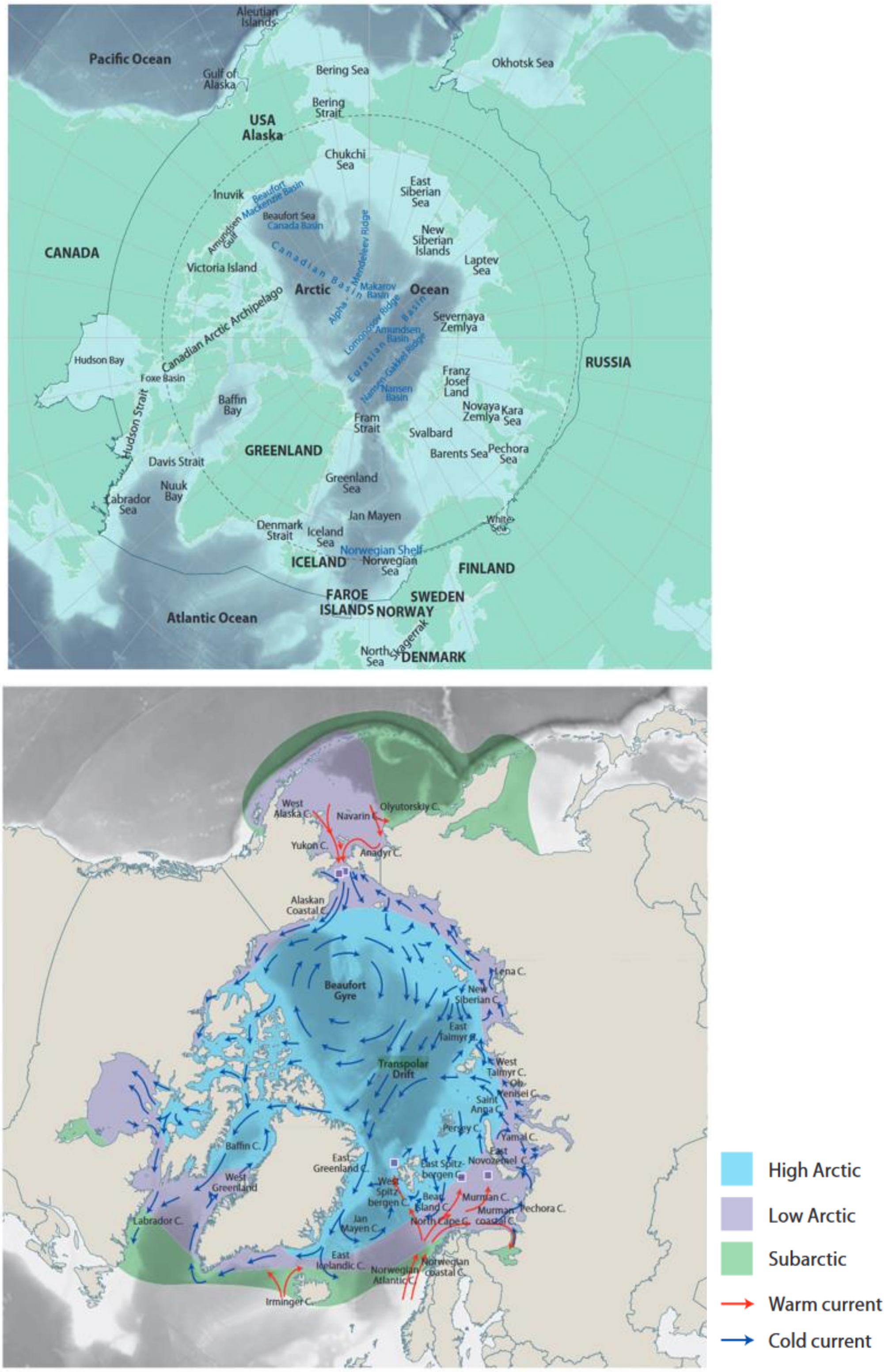



*Figure 3: Maps of the Arctic Ocean and major surface ocean currents. (From AMAP, 2018.)*

### Increased ice export

The region 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 over the past few decades by 6% per decade, and by 11% per decade during spring and summer (Smedsrud *et al*., 2017). During winter months, southward ice export through Fram Strait is highly variable, e.g. fluctuating between 21 $km^3$ per month and 540 $km^3$ per month within a two-month period. This variability is driven primarily by large-scale variability in atmospheric circulation captured by the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) (Ricker *et al*., 2018).

## 2. ACCOUNTING FOR CHANGES IN ARCTIC SEA ICE

### Anthropogenic causes for the changes in Arctic sea ice

Research suggests that at least half of the Arctic's sea ice extent decline since the middle of the 20$^{th}$ century can be attributable to anthropogenic greenhouse gas emissions and the resulting increase in global mean surface-air temperatures (Ding *et al*., 2017; Song *et al*., 2016; Stroeve *et al*., 2012; Kay *et al*., 2011; Notz and Stroeve, 2016; Notz and Marotzke, 2012). Some studies have shown that the decline in Arctic sea ice extent is directly linked to atmospheric $CO_2$ concentration (Stroeve and Notz, 2018; Notz and Stroeve, 2016; Notz and Marotzke, 2012). 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

Much of the melting of sea ice can be attributed to in-situ ocean warming caused by the increased solar absorption (Field *et al*., 2018; 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 eastern 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).

## 3. 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 expansion of the Marginal Ice Zone (MIZ), typically defined as a dynamic area with small ice floes and low ice concentration (15 to 80%) (Aksenov *et al*., 2017; Zhang *et al*., 2015; Strong *et al*., 2017). This widening of the summer MIZ has been estimated at 12% per decade (Strong and Rigor, 2013; Zhang *et al*., 2015) and is projected to continue increasing in the future (Figure 4). The expanding MIZ allows an intensification of the momentum (Martin *et al*., 2016) and heat exchange between atmosphere and ocean (Gallaher *et al*., 2016), enhances solar warming in the upper ocean (Perovich *et al*., 2011), generates stronger ocean surface waves (Overeem *et al*., 2011; Stopa *et al*., 2016; Thompson and Rogers, 2014) and promotes smaller ice floes (Aksenov *et al*., 2017; Hwang *et al*., 2017). These conditions enhance turbulent mixing in the upper ocean (Lincoln *et al*., 2016). By contrast, intense sea ice melt in the MIZ forms a stratified surface layer and subdues the exchanges of momentum and matter between the ocean surface and the deeper ocean (Randelhoff *et al*., 2017).

### Declining sea ice potentially affects primary production and marine wildlife

A seasonally ice-free Arctic can significantly affect primary production (Perovich and Polashenski, 2012). Thinner snow and sea ice increases the light transmission reaching under sea ice (Leu *et al*., 2015), leading to massive under-ice phytoplankton blooms (Arrigo *et al*., 2012). These changes in the phenology and amount of ice-algal and phytoplankton blooms will potentially cascade up the entire Arctic food web (Søreide *et al*., 2010). A modelling study has 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).

Many macro- and mega-faunal species time their feeding (Brown and Belt, 2012) and reproduction (Søreide *et al*., 2010) to coincide with sea ice melt and its associated changes in primary production. Changes in the timing of sea ice formation and melt (including associated changes in primary production) is likely to result in a temporal mismatch of demand for available resources, including carbon available from sea-ice associated algae (Leu *et al*., 2011) and physical habitat (Regehr *et al*., 2016). 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.

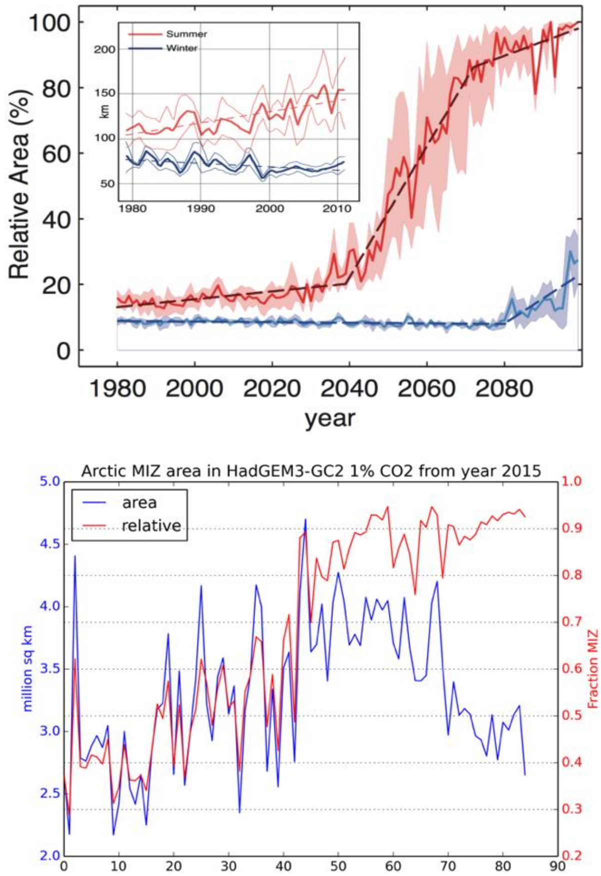



*Figure 4: Simulated monthly mean (solid) relative area (%) of MIZ (sea ice concentration between 15 and 80%) in winter (December-February; blue lines) and summer (June-August; red lines) from the NEMO-ROAM025 projection from Aksenov et al. (2017) (a) and summer ice area (blue lines) together with MIZ relative area (red lines) from a HadGEM3 climate projection (b). The shading in (a) denotes one standard deviation and dashed lines depict fitted linear trends. Inset in (a) shows MIZ width observed by satellites in summer (June-September, red line) and winter (February-April, blue line) taken from Strong and Rigor (2013).*

**Declining sea ice potentially affects remote weather**

There is compelling evidence that reduced Arctic sea ice cover can influence weather and climate beyond the Arctic region (e.g. Kim *et al*., 2014; Kug *et al*., 2015; Kretschmer *et al*., 2016; Francis *et al*., 2017). Sea ice loss in the Barents and Kara Seas has been linked with cold episodes in eastern Asia (Kim *et al*., 2014; Kug *et al*., 2015; Kretschmer *et al*., 2016), has doubled the probability of severe winters in central Eurasia (Mori *et al*., 2014), has increased rain-on-snow events in Siberia causing problems for nomadic reindeer-herders (Forbes *et al*., 2016) and has led to a wavier jet stream (with associated changes in blocking), which has been suggested to link with persistent winter storms in North America (Francis *et al*., 2017).

Sea ice loss has been shown to significantly affect the near-surface air temperature (Ogawa *et al*., 2018) and liquid clouds outside of the summer season (Morrison *et al*., 2018). However, specific mechanisms involved and the extent to which this influence has been manifested (Screen *et al*., 2013; Barnes and Screen, 2015; Ogawa *et al*., 2018), are still the subject of much debate due to the complexity of atmospheric dynamics and uncertainty in the models (Screen *et al*., 2018).

## 3. WHAT COULD HAPPEN IN THE FUTURE?

### Projection of 'summer' ice-free Arctic from climate models

The climate projections of the Intergovernmental Panel for Climate Change Fifth Assessment Report (IPCC AR5, 2014) and many other recent studies suggest that the present trends in sea ice extent / thickness, snow cover, ice drift speed and expansion of the MIZ will continue and accelerate will continue and accelerate, and the Arctic is very likely to be ice-free annually in in September before 2050 under the RCP8.5 emission scenario (Figure 5). If global average temperatures stabilise at 1.5°C above the pre-industrial levels (which, given the current levels of greenhouse gas emission, is looking increasingly unlikely), the chances for an ice-free summer are predicted to be quite low (less than 5%). However, a relatively small rise of global average temperature to 2.0°C is projected to increase the probability of witnessing ice-free summers significantly to 19–34% (Sigmond *et al*., 2018; Jahn, 2018). These probabilities are broadly supported by other studies (Sanderson *et al*., 2017; Ridley and Blockley, 2018; Screen and Williamson, 2017), which provide agreement across climate models that the probability of an ice-free Arctic in summer would substantially reduce if the 1.5°C target of the Paris Agreement (https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27) could be achieved. Even if we restrict global average temperatures to 1.5°C above pre-industrial levels, it might still not be enough to prevent at least one ice-free summer by the middle of the 21st century (Figure 6). If we remain on our current path, projected to cause a 3.0°C warming above pre-industrial temperatures by 2100, this will very likely lead to an ice-free Arctic each summer before the mid-century (IPCC AR5; Rogelj *et al*., 2016).

### Other key projected changes

The intermediate-depth Arctic Ocean will also undergo vigorous changes. The strongest changes are predicted to occur in the Eurasian Arctic Ocean (including Nansen and Amundsen basins). Numerical simulations predict a significant increase of the Atlantic Water inflow into the Eurasian Arctic Ocean (Aksenov *et al*., 2011; Pnyushkov *et al*., 2015), which considerably affect the upper ocean and sea ice properties in that region (Polyakov *et al*., 2017). The Atlantic inflow is expected to be confined within the Eurasian Arctic Ocean, limiting the amount of the Atlantic inflow that enters into 'Amerasian' Arctic Ocean (including Makarov and Canada basins) across the Lomonosov Ridge (Figure 3) (Aksenov *et al*., 2017).

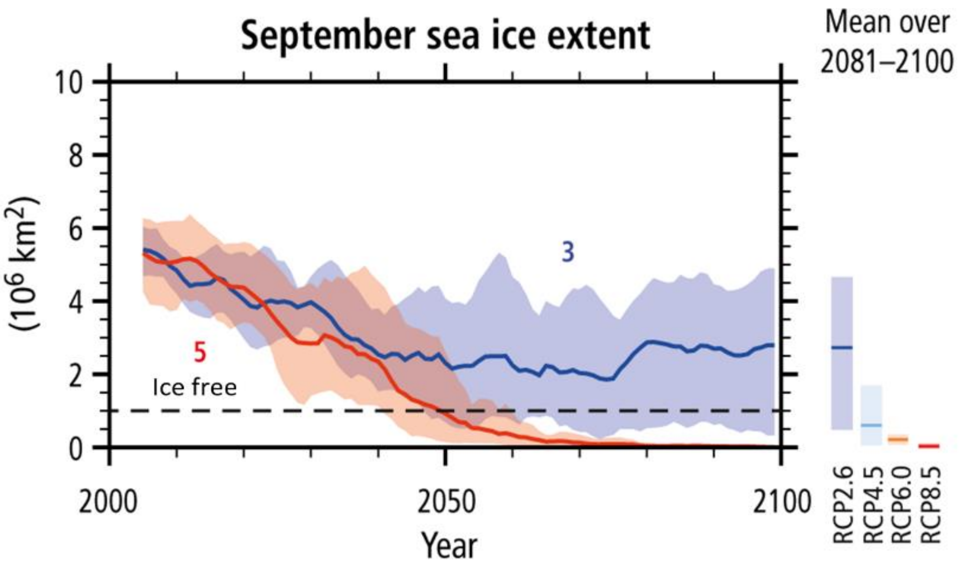



*Figure 5: Change in Northern Hemisphere September sea-ice extent (5 year running mean) under different Representative Concentration Pathways (RCPs). The dashed line represents nearly ice-free conditions (i.e. when September sea-ice extent is less than 1 million km$^2$ for at least five consecutive years). (From IPCC AR5, 2014.)*

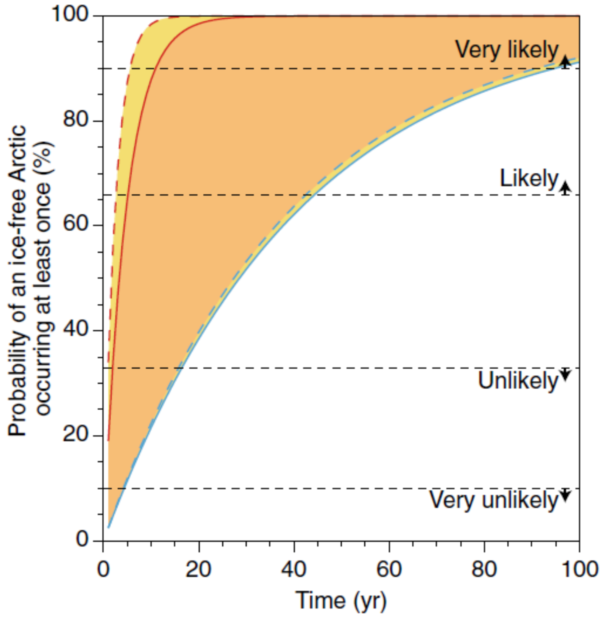


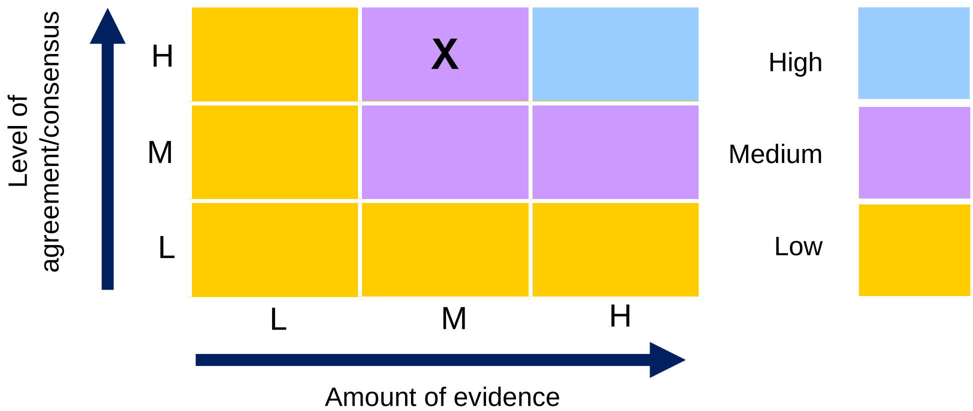

*Figure 6: Probability of at least one occurrence of an ice-free Arctic for stablised global warming of 1.5 ℃ (blue) and 2.0 ℃ (red). (From Screen, 2018.)*

## 4. CONFIDENCE ASSESSMENT

Since the 2013 MCCIP Arctic sea ice report (Giles *et al.*, 2013), the international scientific community has made significant progress in furthering our understanding of the Arctic system. New observational data streams from autonomous robotic platforms, ship-based observations, and satellite sensors, when combined with data from longer time-series, give us a clearer understanding of the rapid changes that are occurring in this important region. It is beyond question that the Arctic is warming, and this warming manifests itself as changes in the ice, ocean, atmosphere and ecosystem. Both observations and models provide strong evidence that considerable changes are happening in the Arctic.

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. The international community are aware of these shortcomings. New observational data sets generated from forthcoming satellite missions (e.g. ICESat-2, RADARSAT Constellation Mission) and international Arctic field campaigns (e.g. MOSAiC, https://www.mosaic-expedition.org) will continue to increase our understanding of Arctic processes further.

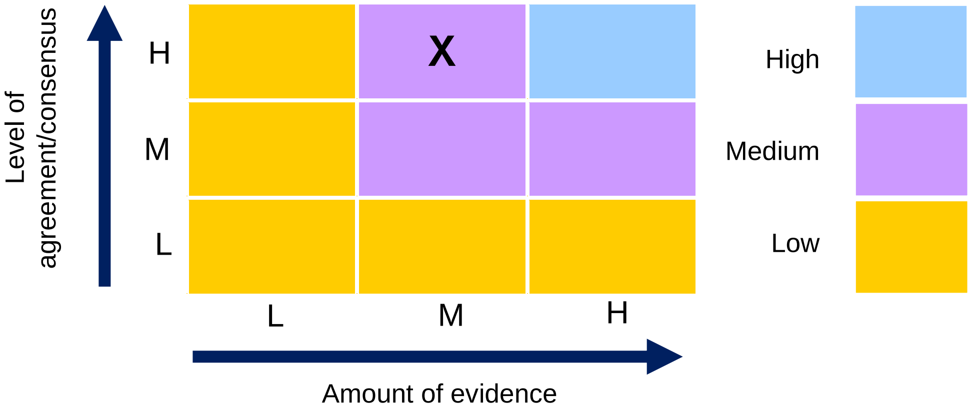
**What is already happening?**




Compared to the 2013 MCCIP Arctic sea ice report (Giles *et al.*, 2013), climate model physics and the level of agreement among ensembles have been improved, yet 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, in saying this, all climate models agree on the downward trend in sea ice extent continuing for the foreseeable future, unless we can limit global warning in line with the Paris Agreement. On that basis, we assess that the level of agreement on an ice-free Arctic with continuing emissions is high. However, the projection of the rate at how specific parameters will change still contains uncertainty and needs improvement. 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 system today, and how it will change in the future.

**What could happen in the future?**




## 5. KEY CHALLENGES AND EMERGING ISSUES

### Arctic shipping

With the continuing Arctic sea-ice reduction by mid-century, summer season sailing times through the North Pole could be as little as 13–17 days or as efficient as through the Northern Sea Route (Aksenov *et al*., 2017). Such shorter sea routes may provide economic gains for the companies and wider economies involved. However, globally the economic gains may not be so favourable. For example, the climatic impact of increased emissions in the Arctic could offset some of the benefit of reduced emissions from the present longer transit routes (Lindstad *et al*., 2016). This is because the use of Arctic routes may lead to increased concentrations of non-$CO_2$ gases, aerosols and particles in the Arctic, which can change radiative forcing both on the surface and in the atmosphere, and cause additional warming (Ramanathan and Carmichael, 2008; Fuglestvedt *et al*., 2014; Aksenov *et al*., 2017). The recent EU funded ICE-ARC programme provided state of the art estimates for the growth of transit shipping on the Northern Sea Route (NSR). Combining these projections with the estimates by Fuglestvedt *et al*. (2014) for the net warming globally from re-routing one unit of ship emissions through the Arctic, Yumashev *et al*. (2017) calculated that the corresponding climate cost could be up to £1.5 trillion over the next two centuries. This offsets around a third of the estimated economic gains associated with the NSR. Increased shipping through the Central Arctic will additionally enhance the probability of a spill of contaminants, for instance of crude oil (Huntington *et al*., 2015). Current procedures for mitigating and cleaning spills in ice-affected waters have their limitations (Afenyo *et al*., 2016; Wilkinson *et al*., 2017). Drifting sea ice can trap oil and transport it long distances, thereby contaminating new regions. Oil slicks beneath ice are very challenging to detect remotely (Firoozy *et al*., 2017), increasing the time and cost of remediation. Use of oil dispersants and in-situ burning are generally much less effective in ice-covered waters (Wilkinson *et al*., 2017). Due to the presence of sea ice, the window for a successful clean-up is short, in the event of a failed recovery, the long-term fate of the unrecovered pollutants must be considered (Kelly *et al*., 2018).

The emerging environmental state of the Arctic Ocean features more fragmented thinner sea ice, stronger winds, ocean currents and waves (Figure 7). Significant wave heights in the Arctic Ocean have considerably increased for the last 20 years, at the rate of around 7–10% per decade (Stopa *et al*., 2016; Thompson *et al*., 2016) and are projected to increase in the 21st century by 100–500%, reaching heights in excess of 3 m in the Arctic shelf seas (Francis *et al*., 2011; Khon *et al*., 2014; Aksenov *et al*., 2017). The transformation into a seasonally ice-free Arctic results in different challenges for marine operations and forecasting systems. Specifically, the combined impact on the ship structures from wave and ice floes and icing spray deposition on the upper decks become major hazards for ships.

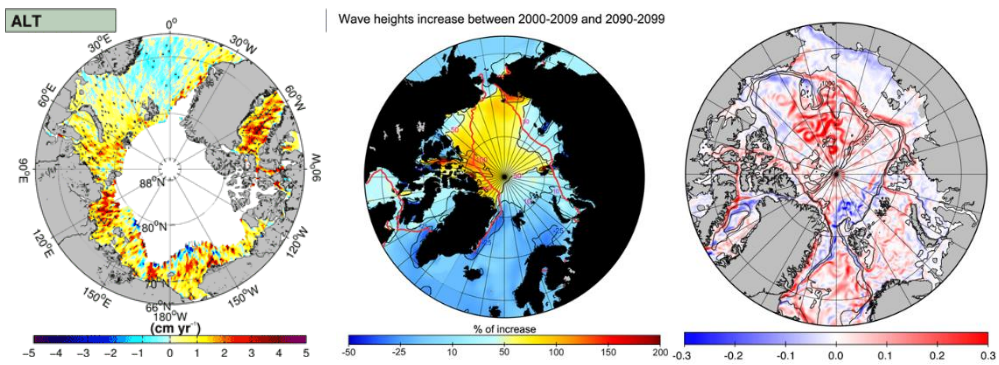



*Figure 7: Observed trends in significant wave heights 1992–2014 from Stopa* et al. *(2016) (a) along with the projected significant wave heights increase (b) and increase in the speed of the ocean surface currents (c) from the 2000s to the 2090s. (From Aksenov* et al.*, 2017.)*

## Coastal erosion and permafrost decay

A sharp intensification in erosion of the northern Alaskan coast has been observed, with mean annual coastal retreat of around 14 m per year in the 2000s compared with 9 m per year during 1970s–1990s (Jones *et al*., 2009;

Lawrence *et al*., 2008). This intensification is caused by the increasing storms, wave fetch and wave heights (Khon *et al*., 2014; Overeem *et al*., 2011; Thomson *et al*., 2014, 2016) due to the sea ice decline, Arctic Ocean surface warming and sea-level rise (Stopa *et al*., 2016). In the Laptev Sea, the mean annual erosion rates have increased in recent years (6.5 ± 0.2 m per year) compared to the long-term mean (2.2 ± 0.1 m per year), with large variations due to local coastal relief (Gunter *et al*., 2013). The higher erosion rate has led to greater quantities (up to 46.5 Gt per year) of organic carbon being released to the near-shore zone of the Arctic shelves. The carbon release will be considerably higher if recent rapid coastal erosion rates persist. In a warmer Arctic, potentially rapid permafrost thawing and carbon decomposition can discharge a large amount of carbon accumulated for a long time. This irreversible carbon decomposition can further increase atmospheric $CO_2$ and $CH_4$ concentrations. Recent observations suggest that this is already occurring (Collins *et al*., 2013; Biskaborn *et al*., 2019).

**Changing marine ecosystem**

Changes in the sea ice and ocean are expected to affect Arctic ecosystems, fisheries and local industries and the local Arctic indigenous population (http://www.uarctic.org/). The primary productivity in the Eurasian Arctic has significantly increased by 35% for the period of 2003–2017 (Frey *et al*., 2017). This increase in primary production is attributed to more light availability due to the loss of sea ice (Fernández-Méndez *et al*., 2015; Yool *et al*., 2015), caused by Atlantic inflows (Polyakov *et al*., 2017). In contrast, the primary production in Amerasian Arctic has shown no significant increase for the same period (Frey *et al*., 2017), despite increased light availability due to sea ice loss in that region. This can be attributed to the limited inflow of nutrient-rich Pacific water to the Amerasian Arctic by the low connectivity through Bering Strait (Clement Kinney *et al*., 2014; Aksenov *et al*., 2016). The projected decoupling of the circulation systems in the Eurasian and Amerasian Arctic basins suggests a reduced flow of nutrients between the basins and a stronger separation between the ecosystem in the Eurasian and Amerasian Arctic Ocean in the future (Aksenov *et al*., 2017).

Atlantic species will gain increasing access to higher latitudes as their preferred temperature ranges expand further north as sea ice retreats (Neukermans *et al*., 2018; Renaud *et al*., 2015). Accordingly, sub-Arctic ecosystem structures are already being re-organized (Brown *et al*., 2017; Kortsch *et al*., 2018), which may lead to the displacement of specialist Arctic species. Such alterations could also be economically disruptive where Arctic species provide commercial income. The, currently unknown, extent of such impacts has triggered key nations to agree to prohibit commercial fishing in the high seas of the Arctic for at least 16 years to allow scientists time to better predict the sustainability of fish stocks.

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