The Arctic's sea ice cover: trends, variability, predictability and comparisons to the Antarctic

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Short title: Variability, trends and predictability of sea ice

Graphical abstract

As assessed over the period of satellite observations, October 1978 to present, there are downward linear trends in Arctic sea ice extent for all months, largest at the end of the melt season in September. The ice the cover is also thinning. This review describes the downward trends in Arctic sea ice extent, and the variability superposed upon these trends. Attention then turns to seasonal and longer-term predictability of Arctic seas ice conditions, including projections through the 21st century. The sharp contrast between the trends in Arctic and Antarctic sea ice extent is then addressed.

Abstract

As assessed over the period of satellite observations, October 1978 to present, there are downward linear trends in Arctic sea ice extent for all months, largest at the end of the melt season in September. The ice the cover is also thinning. Downward trends in extent and thickness have been

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/nyas.13856.

accompanied by pronounced inter-annual and multi-year variability, forced by both the atmosphere and ocean. As the ice thins, its response to atmospheric and oceanic forcing may be changing. In support of a busier Arctic, there is a growing need to predict ice conditions on a variety of time and space scales. A major challenge to providing seasonal scale predictions is the 7–10 day limit of numerical weather prediction. While a seasonally ice-free Arctic Ocean is likely well within this century, there is much uncertainty in the timing. This reflects differences in climate model structure, the unknown evolution of anthropogenic forcing, and natural climate variability. In sharp contrast to the Arctic, Antarctic sea ice extent, while highly variable, has increased slightly over the period of satellite observations. The reasons for this different behavior remain to be resolved, but responses to changing atmospheric circulation patterns appear to play a strong role.

Keywords: Arctic; Antarctic; sea ice; trends; variability; predictability

Introduction

Sea ice is a dominant feature of the high latitude oceans. The most common measure of sea ice is extent, defined as the area covered with an ice concentration (fractional ice cover) of at least 15%. Extent waxes and wanes with the seasons. The median Arctic extent, as assessed over the period 1981 to 2010, is greatest in mid- March (around 15.6 x 10^6 square km). The minimum median extent of around 6.2 x 10^6 square km falls in mid-September (Figs. 1 and 2). For comparison, the contiguous United States has an area of 8.1 x 10^6 square km. Ice thickness ranges from a thin veneer to occasionally more than 5 meters. While the term "Arctic ice extent" is ingrained in the literature, extent numbers typically cited, like those above, include all Northern Hemisphere sea ice. At or near the seasonal maximum, sea ice is found well south of the Arctic Circle, covering all of Hudson Bay and part of the Bering Sea, the Sea of Okhotsk, the Baltic Sea and the Gulf of St. Lawrence. It is occasionally found as far south as the Bohai Sea and Chesapeake Bay (~40° N latitude). Similarly, "Antarctic ice extent" includes all Southern Hemisphere ice. The Antarctic seasonal cycle is more pronounced; the maximum typically occurs in late September (around 18.7 x 10^6 square km) and the minimum is in late February (2.8 x 10^6 square km) (Figs. 1 and 2). In general, Antarctic sea ice is thinner than that found in the Arctic.

Most of the ice cover is in constant motion, primarily under the influence of winds and ocean currents. The mean circulation of the Arctic sea ice cover (Fig. 3) is dominated by the Beaufort Gyre, a clockwise drift centered over the Beaufort Sea, and the Transpolar Drift Stream, a pattern of drift from the coast of northern Eurasia, across the pole and out of the Arctic Ocean via Fram Strait. These features are broadly consistent with the wind pattern inferred from the mean sea level pressure distribution (winds blow roughly parallel to lines of equal pressure, known as isobars). The drift tends to have a slight onshore component along the coasts of the Canadian Arctic Archipelago and Northern Greenland, favoring the formation of pressure ridges and accompanying underwater keels. Hence the thickest ice in the Arctic Ocean can be found in this region. However, due to variable winds and ocean currents, ridging and keel formation occur essentially anywhere. By contrast, divergent ice motion results in roughly linear openings, called leads. In winter, leads may quickly freeze over. Irregularly shaped openings also develop. Where these occur regularly and persist, due to upwelling of warm ocean waters or winds blowing ice away from a barrier (coast, ice shelf, or landfast ice), they are called polynyas.

The satellite passive microwave record has provided consistent estimates of Arctic and Antarctic sea ice extent since October 1978. This record combines data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR, October 1978–1979) and an overlapping series of Defense Meteorological Satellite Program (DMSP) sensors: the Special Sensor Microwave/Imager (SSM/I, 1987–2007) and the Special Sensor Microwave Imager/Sounder (SSMIS, 2008–present).[1] The microwave record documents downward linear trends in Arctic ice extent for all months, smallest in winter and largest for September (Fig. 4). Over the period 1979–2017, the September trend is about -83,000 square kilometers per year, or -13.0% per decade as referenced to the mean September extent for 1981–2010. The ice cover is also thinning.[2–6] Using earlier forms of satellite data, ship and aircraft reports, a longer record of monthly Arctic ice extent has been assembled back to the early 1950s.[7] Efforts have also been made to extend the Arctic record back to 1850[8,9] and paleoclimate reconstructions provide information on summer extent spanning almost 1500 years.[10] The satellite-era trends appear to be unprecedented. Antarctic extent over the satellite record has a slight upward trend, but with high temporal and regional variability. Insufficient data exist to extend the Antarctic record to earlier years.

Discussion that follows describes the downward trends in Arctic sea ice extent, and the variability superposed upon these trends. Attention then turns to seasonal and longer-term predictability of Arctic seas ice conditions, including projections through the 21st century. The sharp contrast between the trends in Arctic and Antarctic sea ice extent is then addressed.

Trends and variability

Overview

To understand trends and variability in the Arctic sea ice cover, it is useful to first draw comparisons with the 100-plus year record of global average surface-air temperature. The upward trend in global air temperature is interpreted as primarily a forced response to rising concentrations of atmospheric carbon dioxide and other greenhouse gases, with the ups and downs from year to year (and even decade to decade) interpreted as expressions of natural climate variability. This variability has many origins, including the phase of the El Niño Southern Oscillation and Arctic Oscillation, the strength of the Atlantic Meridional Overturning Circulation, solar variability and the injection of sulfate aerosols into the stratosphere from volcanic eruptions (an example being Mt. Pinatubo in 1991). The global value for a given year or month averages together areas with positive and negative anomalies in temperature, and the regional anomalies can be large enough to affect the global average. The time series of Arctic sea ice extent can be similarly viewed. There are downward trends in all months (Fig. 4), interpreted as forced by a warming climate. As with interpretation of the trend in air temperature, much of this evidence comes from simulations with coupled global climate models. These simulations show that without the observed increase in atmospheric greenhouse gases, one cannot get a downward trend in September ice extent (or an upward trend in temperature) like that which is observed.[11,12] Second, there are ups and downs in ice extent from year to year, and even for runs of years, reflecting the natural variability superposed upon the linear trends. Third, in any given year or month, the total extent is an average of regions with positive and negative anomalies in extent, and the regional anomalies can be sufficiently pronounced to affect the Arctic average.

Beyond these general points, the similarity breaks down. Three issues stand out, summarized below and expanded upon in subsequent sections:

- There is distinct seasonality in the strength of both the linear trends in extent and variability about the trends. Trends are smallest in winter, become larger through spring and summer and into September, then become smaller again through autumn. Variability follows the same basic pattern;
- Variability in extent reflects coupling between thermodynamic forcing that affects ice growth and melt and dynamic forcing that affects patterns of ice motion. This forcing originates in both the atmosphere and the ocean;
- There is growing evidence that thinning of the ice cover is changing its response to natural climate variability.

Seasonality in trends and variability

The pronounced seasonality in the strength of the downward trends in Arctic sea ice extent over the period of satellite observations (Fig. 4) is in part a consequence of the distribution of the continents.[13] The Arctic Ocean is somewhat like the Mediterranean Sea in that it is largely landlocked. In winter, even in a warming climate, it gets cold enough so that ice expands southward until it encounters land. This blocking mutes changes in ice extent. Such blocking has less of an effect in summer because the ice largely recedes away from the coast. Without a land constraint, winter extent would be greater than observed, but would also be free to shrink through time in response to a warming climate. In support of this view, Eisenman[13] finds that if one focuses on those areas where the ice is free to expand southward in winter (Atlantic side, the Bering Seas, the Sea of Okhotsk) the zonal mean latitude of the ice edge is migrating north at a fairly consistent rate between seasons.

Thinning of the ice cover also plays a role. The sea ice cover is not a featureless slab, but is a mélange of different ice age classes. Ice that forms in a single growth season is called first-year ice. Much of this first-year ice melts away in summer, but some survives, and that which does can further thicken over the next winter, mostly through growth at the bottom of the ice. Some of this second year ice may in turn survive the next summer melt season, and so on. Any ice surviving at least one melt season is called multiyear ice. Generally, the older ice is the thicker ice. This is not a hard rule—thin first-year ice can easily ridge, forming thick ice, and this ridged ice is most likely to survive the first melt season—but the relationship between age and thickness holds in general.[2]

Over the past several decades, the Arctic has progressively lost much of its thick multiyear ice.[2,14] While part of the loss is due to melt, the more dominant process is that in the warmer climate, multiyear ice that is exported out of the Arctic through Fram Strait is not being fully replaced. With loss of the older age classes, at the start of the melt season, the first-year ice comprises a progressively larger fraction of the total ice cover (Fig. 5). This first-year ice is especially prone to melting out through spring and summer, hence yielding trends in extent that grow in magnitude into September.

Because of the pronounced seasonality in the size of the trends, the seasonal cycle in Arctic ice extent has become increasingly pronounced and is hence starting to look more like that observed for the Antarctic, where there is a great deal of ice growth in autumn and winter, but comparatively little survives the summer melt season. By definition, when all of the multiyear ice is gone, the Arctic will have become what is termed "seasonally ice free". That is, there will be a period in late summer to early autumn when there is little or no sea ice. There is general consensus within the community that a seasonally ice-free Arctic means less than 1.0×10^6 square km of ice.

It is also apparent from Figure 4 that the ups and downs in extent from year to year—the variability—is also larger in summer than in winter. Again, this points to blocking by land[13]—since in winter, the ice extent will only tend to vary in those areas where it is unbounded, the variability in extent for the ice cover as a whole will tend to be fairly small. By comparison, as the ice retreats in spring and summer, it is less bounded by land, so the edge is increasingly free to vary. Note that in all seasons, ice is essentially always bound to the shore along the northern coasts of the Canadian Arctic Archipelago and Greenland. This reflects the mean pattern of onshore ice motion in these areas discussed earlier.

Variability for September, the month with the minimum ice extent, has received the most attention. As reviewed by Serreze and Stroeve[15], this variability is impressive. Year-to-year excursions of the September average extent during the satellite record may exceed 1.0 x 10^6 square km. One of the highest September extents, 7.58 x 10^6 square km, occurred in 1996; this was 1.5 x 10^6 square km higher than the value for the previous year, 1995 (a relative increase of 25%). Extent then dropped by nearly a million square km between 1996 and 1997. The second lowest September extent in the satellite record of 4.27 x 10^6 square km, recorded in 2007, was 1.59 x 10^6 square km below the 2006 value, a relative decrease of 27%. The record minimum monthly extent of 3.57 x 10^6 square km recorded in 2012 was followed in 2013 by a value of 5.21 x 10^6 square km, nearly a 50% increase.

Drivers of variability

Variability in ice extent for any given month, whether for the Arctic as a whole or by region, is strongly shaped by anomalies in atmospheric circulation patterns, especially those persisting for a month or longer. The ocean also plays a strong role. Most attention has been paid to understanding variability in September (or summer) extent but there is ample interest in winter anomalies.

Investigations of atmospheric forcing have ranged from case studies[16–21] to the role of large-scale patterns of atmospheric variability (often referred to as modes of variability). Key among these are the Arctic Oscillation (AO)[22–24], its close cousin the North Atlantic Oscillation (NAO)[25] and the Arctic Dipole Anomaly.[26] Other investigators have looked at the problem using various compositing approaches[27,28], where, for example, one looks at average atmospheric patterns associated with positive anomalies in extent and contrasts these with average atmospheric patterns associated with negative anomalies in extent. Some studies indicate that summer circulation patterns over the Arctic are a significant driver of the summer sea ice cover variability (Ding et al., 2017; Wernli and Papritz, 2018).[29,30] Studies of ocean forcing have focused on the heat inflows from both the Pacific[31] and the Atlantic.[32,33]

Three key conclusions can be drawn:

1. Responses of the sea ice cover to atmospheric forcing involve both dynamic and thermodynamic components that often have reinforcing influences. With respect to dynamic influences, variations in the wind field can variously force offshore ice motion, resulting in regional reductions in ice extent or thickness[22], or onshore motion, with the opposite effect.

Thermodynamic influences involve processes that affect surface energy exchanges. For example, winds from the south also tend to be warm winds that can limit winter ice growth or hasten summer melt. Winds from the south also tend to carry water vapor into the Arctic, which can result in more downward longwave radiation to the surface through the increase in atmospheric emissivity, either from the water vapor itself or from increased cloudiness.[34] Snowfall can be important, either through raising the surface albedo (the reflectivity of the surface in the wavelengths of solar radiation), or providing an insulating layer because of its low thermal conductivity, reducing winter ice growth. Anomalies in temperature and snow cover can affect the coverage of summer melt ponds, influencing summer melt rates through reducing the surface albedo (reflectivity).[35]

2. As a broad statement, years with low September sea ice extent for the Arctic as a whole, when assessed as departures from the linear trend line, tend to occur when the preceding summer is characterized by high pressure over the central Arctic Ocean. Septembers with higher extent relative to the trend line tend to occur when the preceding summer is characterized by low pressure over the central Arctic Ocean.[24,31] However, even small shifts in pressure centers can lead to very different patterns of September ice extent[36], and the response of the sea ice to atmospheric forcing may be changing.

3. Large departures in September extent relative to the linear trend line seldom persist for more than a couple of years (Fig. 6). While there is a strong one-year autocorrelation in the September extent time series that results from the downward trend, when the time series is de-trended, the one-year lag autocorrelation for September is essentially zero.[15] Phrased differently, with respect to extent, there is little inherent "memory" in the system from one September to the next.

To illustrate the basis of these conclusions, it is useful to start by considering the role of atmospheric forcing during summer. As early as 1945, it was recognized that cyclone activity (the frequency of low pressure systems) over the central Arctic Ocean peaks during summer.[37] This summer peak arises from storms generated over the Eurasian continent that migrate into the central Arctic Ocean where they eventually stall and dissipate, as well as cyclones generated over the Arctic Ocean itself.[38,39] The pattern is highly variable. Summers when the central Arctic Ocean cyclone pattern is well expressed are characterized by a summer-averaged low-pressure area centered near the pole. When the cyclone pattern is not well expressed, high pressure (a mean anticyclone) prevails. As noted above, the cyclonic pattern tends to favor retention of sea ice through the summer while the anticyclonic pattern tends to have the opposite effect. Ogi and Wallace[24] captured this contrast in the framework of the "summer AO" pattern. Regarding dynamic influences, this relationship is consistent with the idea that under "free drift" conditions—when floe-to-floe interactions are small, a cyclonic wind pattern will tend to give rise to a pattern of ice divergence[40], spreading out the ice to cover a larger area. As for thermodynamic influences, the cyclones found in this area in summer tend to be cold-cored decaying systems, with the generally cold conditions inhibiting summer melt. Precipitation that falls may be in the form of snow, raising the surface albedo. By contrast, when high pressure (anticyclonic conditions) dominates, this favors ice convergence, and temperatures in the lower troposphere tend to be above average.[41]

The negative phase of the summer AO pattern has similarities to a pattern that has come to be known as the Arctic Dipole Anomaly, or DA.[26] Atmospheric conditions during the summer of 2007 serve as the exemplar of the DA pattern and provide another example of the interplay between dynamic and thermodynamic influences (Fig. 7). September of 2007 has the second lowest sea ice extent in the satellite record. In considerable part, this is attributed to a pattern of atmospheric circulation at the surface persisting through the summer, pairing a fairly strong anticyclone (high pressure area) with low pressure centered over northeastern Eurasia.[20] In the Northern Hemisphere, winds blow broadly clockwise around anticyclones and clockwise around low pressure areas (roughly along the isobars—lines of equal pressure). Because of these relationships, the pressure pattern that set up in the summer of 2007 led to persistent winds with a component from the south over the Chukchi Sea and East Siberian seas. While this led to very warm conditions in this area, favoring strong summer melt, at the same time the wind pattern pushed the ice edge poleward. The association between the area with winds from the south and the areas of "missing" ice is obvious (Fig. 7). Furthermore, on the Atlantic side of the Arctic, the pattern of sea level pressure led to winds from the north that favored a strong transport of ice through Fram Strait and into the North Atlantic, where it eventually melted.

Overland et al.[42] showed that for the period 2007–2012, there was a persistent DA pattern in the June sea level pressure fields, suggesting a change during that time towards conditions favoring summer ice loss. A more recent analysis[36] for the period 1979–2015 shows statistically significant increases in summer sea level pressure north of the Canadian Arctic Archipelago and Alaska and for the region over and surrounding the Greenland Ice Sheet, attended by significant negative trends over northern Eurasia. The trend pattern broadly resembles the sea level pressure anomaly pattern for the summer of 2007. However, this trend may have broken down; the summers of 2016 and 2017 were both characterized by strongly cyclonic conditions over the central Arctic Ocean.

Studies by Rigor et al. and Rigor and Wallace[22,23] illustrate how September ice extent can respond to atmospheric forcing the previous winter. Both efforts adopted the framework of the winter AO pattern. The summer AO pattern discussed earlier is dominated by a single "center of action" centered near the pole. By contrast, the winter pattern[43], has three centers of action, one centered near Iceland (the Arctic center), with the other two of opposite sign, centered over the North Atlantic and North Pacific. The interpretation is that if pressures are low over the Arctic center, they are high over the North Atlantic and Pacific centers (the positive AO phase), and vice versa (the negative AO phase). The winter AO is very similar to the long-recognized North Atlantic Oscillation (NAO) which is an expression of co-variability in the strengths of the Icelandic Low (basically, the locus of Arctic AO center of action) and the Azores high, closely corresponding the North Atlantic center in the AO.

The phase of the winter AO changed from generally negative values in the 1970s to positive values through the 1980s and 1990s; the NAO index underwent a very similar change.[43] Rigor et al.[22] showed that as the winter AO trended towards its positive phase, changes in the surface wind fields led to a change in the sea ice motion, tending to both transport ice away from the Siberian and Alaskan coasts and (because of the cyclonic tendency) promote more ice divergence (a dynamic response). These dynamic responses led to an anomalous coverage of thin ice. With thinner ice in spring, less energy was needed to melt out the ice (a thermodynamic response), setting the stage for large negative anomalies in summer ice extent along the Alaskan and Siberian coasts (reflected as anomalies in total summer Arctic ice extent), that started to be observed in the 1990s. Subsequently, Rigor and Wallace[23] found that surface wind patterns associated with positive AO conditions that were particularly dominant over the period 1989–1995, decreased the area extent of old thick ice over the Arctic Ocean, mostly via transport through Fram Strait (the dynamic effect). The Arctic Ocean was then left with more young and thin ice. During the summers of 2002 and 2003, this younger, thinner ice circulated back into Alaskan coastal waters via the Beaufort Gyre circulation, where extensive ice melt occurred (the thermodynamic effect). In 2007, the preceding winter AO was moderately positive, but as noted above, the low 2007 summer extent was largely driven by the summer circulation pattern (Fig. 7a).

Turning to the ocean, heat inflow through the Bering Strait has long been implicated in the seasonal melt-back of ice in the Chukchi Sea region.[44–49] This inflow is driven by a difference in oceanic pressure (often called the "pressure head") between the Pacific and the Arctic Ocean, but is strongly modulated by local wind patterns.[50] The inflow has a pronounced seasonal cycle, smallest in winter and largest typically in August or September. The seasonal maximum is driven by both the higher water temperatures in summer as well as a general summer maximum in water volume transport.[51] An upward trend in the heat inflow noted by Woodgate et al.[52] over the period 2001 to 2010 appears to be continuing.

On the other side of the Arctic, warm Atlantic waters enter the Arctic Ocean through eastern Fram Strait and the Barents Sea. As noted by Schlichtholz[53], much of the variability in sea ice extent in the Nordic seas is explained by the temperature of Atlantic waters in the Barents Sea. However, once this warm and salty Atlantic water enters higher latitudes, it sinks underneath the relatively fresh (hence low density) surface waters of the Arctic Ocean, forming an intermediate layer. While the cold halocline layer (where density increases strongly with depth) separating the Atlantic and surface waters insulates the sea ice from the Atlantic layer heat, it is increasingly recognized that some of this Atlantic heat can be brought to bear to both limit ice growth and hasten bottom melt. There was a general increase in the Atlantic heat inflow starting in the early 1990s[54,55] that continued into the first decade of the 21st century. [32,33,56] Adding to the complexity, the strength of the insulating cold halocline appears to be quite variable.[57,58] In recent winters, ice-free conditions in the Barents Sea and the vicinity of Svalbard, where the Atlantic inflow subducts under the cold halocline, have extended further north as compared to past decades.[56] Polyakov et al.[59] show that while the inflow of Atlantic waters has actually slowed since peaking in 2008, its influence on the sea ice cover has only become more prominent, apparently through weakening of the cold halocline.

Changing responses

It is reasonable to expect that as the sea ice cover thins, the sea ice response to atmospheric forcing will also change. For example, with thinner spring ice, atmospheric circulation patterns favoring summer ice loss ought to become more effective in doing so, because less energy is needed to melt out areas of ice and thinner ice is more mobile. Studies have shown an increase in sea ice drift speed but not change in wind speed, indicating that the ice is becoming more responsive to winds as it thins.[60–62] Faster ice drift results in greater export of ice through Fram Strait and also fosters further thinning. Such "preconditioning" has been speculated as a factor helping to explain the extreme summer sea ice retreat observed in 2007[20]; had the same DA pattern set up 30 years ago when the ice was thicker, the anomaly in ice extent at summer's end would have been much smaller.

Predictability

Timescales and sources of predictability

As the Arctic Ocean loses its ice cover, it becomes more accessible to marine shipping, extraction of oil and natural gas deposits and tourism. However, even in a warmer Arctic, ice conditions will be highly variable, and there will likely be winter ice for centuries. As such, there is a growing need for improved predictability of sea ice conditions. At the tactical level (e.g., to plan for re-supply of ports and support other marine traffic), needs range from short-term forecasts of regional ice conditions to predicting seasonal ice retreat dates and the open water period in key areas such as the Chukchi Sea, Northwest Passage and Northern Sea Route.[63] Strategic planning, such as planning for when the Northwest Passage will become reliably open in summer, requires predictability on decadal and longer time horizons. Stakeholders tend to require information at the regional scale. By contrast, within the science community, much of the focus has been on the scale of the Arctic sea ice cover as a whole. However, efforts are growing to provide spatial maps of ice retreat to inform regional predictions.[64] In the longer-term, estimating when the Arctic Ocean will become seasonally ice-free has been the topic of numerous studies.

As discussed, the atmosphere is a key driver of sea ice variability. However, as a source of predictability, its value is at present largely limited to the 7- to 10-day timescale of numerical weather prediction (NWP). This still has high value. For example, to support its operations, the U.S. Navy provides nowcasts up through 7-day forecasts of sea ice concentration, thickness and motion via its Global Ocean Forecast System (GOFS 3.1).[65] Efforts are ongoing within NOAA to provide seasonal outlooks of general weather patterns that could be applied to sea ice forecasting. For example, knowing on June 1 that the next two months are likely to be dominated by an Arctic Dipole Anomaly pattern[26] could help in predicting September ice extent, even at the regional scale valued by stakeholders. However, seasonal weather outlooks at present have limited skill in the Arctic and beyond the 7- to 10-day timescale of NWP. Consequently, unpredictable atmospheric anomalies degrade the skill of seasonal ice forecasts. Uncertainty can be reduced by implementing bias-correction and other adjustment to models to better match observed initial conditions, such as of ice thickness. Seasonal forecast methods tend to work best for years when extent falls near the long-term trend, but struggle when there are large excursions from the trend.[66]

The value of ocean conditions as predictor on seasonal timescales is that ocean anomalies tend to persist and can have strong regional impacts. For example, and as already noted, Schlichtholz et al.[53] find that much of the variance in winter sea ice extent in the Nordic seas is explained by the temperature of Atlantic waters in the Barents Sea. On the other side of the Arctic, more than half of the variance in the date of seasonal ice retreat in the Chukchi Sea (based on detrended anomalies) is explained by the Bering Strait heat inflow averaged from April through June.[31]

Albedo feedback and ocean heat uptake provide another source of predictability[31,67–69]. In the framework of Guemas et al.[70] this could be viewed as a “re-emergence” mechanism. Briefly, as solar radiation increases and air temperatures rise in spring, surface melt drops the albedo, accelerating ice melt. Eventually, dark open waters are exposed, becoming more extensive as the melt season progresses. These areas readily absorb solar radiation, increasing internal energy storage in the ocean mixed layer. Before sea ice can form again in autumn, this internal energy must be lost to the atmosphere and to space. If in a given region, an open water area develops earlier than average, the seasonal ocean heat uptake increases—earlier melt leads to an earlier drop in the ice albedo, meaning earlier and longer exposure of open water in areas that normally open later in the year. As the spring-summer energy uptake increases, so will the delay in autumn ice growth because it takes longer for the ocean to lose the absorbed heat. An unusually late retreat will have the opposite effect. In other words, if the ice retreats early its seasonal advance will tend to be late, and vice versa.

The initial anomaly which albedo feedback and ocean heat uptake feed upon can have a number of sources. Early melt onset, for example, has been linked to influx of moist (and hence typically cloudy) air masses that increase the longwave radiation flux to the surface.[34] Anomalies in the spring surface melt onset[71] or melt pond fraction[35] atop the sea ice, potentially driven by both (or either) snowfall or temperature anomalies, can provide a source of predictability through their influences on surface albedo. Anomalies in the Bering Strait or Atlantic heat inflow represent other sources. In a similar vein, knowledge of September ice extent can potentially be improved by knowing the springtime distribution of ice thickness—thick ice will have a greater tendency to survive than thin ice.[72,73]

Approaches to seasonal-scale forecasting at the Arctic-wide and regional scale range from heuristic methods to statistical models and the use of coupled climate models. The Sea Ice Prediction Network (https://www.arcus.org/sipn) provides a forum for comparing seasonal forecasts from various approaches. However, to reiterate, the skill of seasonal forecasts from predictors such as those described above continues to be limited by the unpredictability of weather patterns beyond 7 to 10 days.

Towards a seasonally ice-free Arctic Ocean

Turning to longer timescales, the questions of when the Arctic Ocean will become seasonally ice-free and the trajectory that it will take have largely been approached using coupled global climate models. Two key conclusions emerge: (1) through a combination of model biases, natural variability and unknown future greenhouse gas emission rates, considerable uncertainty remains as to when seasonally ice-free conditions will be reached, and (2) the trajectory is likely to resemble that which is being observed, characterized by large variability superposed upon a downward trend in extent.

Most studies have made use of either: (1) multi-model ensembles, whereby projections from a suite of different models using the same greenhouse gas emissions scenario are viewed individually and as a group, or (2) single-model ensembles, in which projections from the same model are obtained from a number of simulations that each start from very slightly different initial conditions. In a multi-model ensemble, there may be multiple ensemble members from an individual model that are variously averaged together or viewed individually. The multi-model ensemble approach yields a series of projections for a given emissions scenario that capture both the uncertainty due to different model physics (model structure) and natural variability while the single-model ensemble captures the uncertainly with a given emissions scenario associated with natural variability.

Typically, projections for a given emissions scenario are extended from hindcasts, in which simulations are driven by estimates of historical climate forcings (e.g., greenhouse gas emissions, aerosol forcing from volcanic eruptions, solar variability). Hindcast simulations are valuable because they enable assessment of how well the historical simulations of sea ice extent (or other variable of interest) compare to what has actually been observed. If a model can reasonably simulate the historical record (e.g., mean extent, forced trends), this lends confidence in the projections of future conditions. In some studies[74–76], models that perform poorly over the period of direct observations, such as having ice extent or trends in extent very different from that which is observed, are eliminated from consideration, the intent being to reduce the uncertainty (spread) in the projections. The validity of such approaches remains controversial.

A widely cited example of a multi-model ensemble approach is Stroeve et al.[74] who looked at both hindcasts and projections from a suite of models participating in the IPCC 4th Assessment (AR4). They used only those models with mean extent within 20% of observations. They found that nearly all of the selected models simulated downward trends in sea ice extent over the period of observations (1963–2006) but as a group the trends were smaller than observed. While raising speculation that the strong observed September trend is a statistically rare event in which imprints of natural variability (e.g., influences of the AO) dominate over any influence of greenhouse gas loading, it was also emphasized that as a group, the models may be deficient in their response to greenhouse gas forcing. This argued that the model projections of the timing of an ice-free Arctic Ocean under the assumed "business as usual" emissions scenario might be too conservative and that a seasonally ice free Arctic Ocean might be realized in only a few decades.

A later study[77], using output from the next generation of models participating in the IPCC 5th Assessment, showed better agreement between observed and simulated trends. However, based on all simulations from all models, including individual ensemble members from models for which they were available, no screening, and adopting the Representative Concentration Pathway (RCP4.5) emissions scenario, an essentially ice-free September could be realized as early as the year 2020 or well beyond the year 2100 (Fig. 8). The RCP4.5 scenario essentially represents a top of atmosphere radiative forcing of 4.5. W m^{-2} (relative to pre-industrial conditions) by the year 2100. Even assuming the most aggressive forcing scenario (RCP8.5) there is a spread between projections between different models and their ensemble members of more than 100 years[78], reflecting a combination of model biases and natural variability.

Based on model selection criteria, Liu et al.[76] offer that under the RCP8.5 scenario, September extent will drop to about 1.7 million square kilometers in the mid-2040s with ice-free conditions (less than 1.0 x 10^6 square km) in the 2060s, followed by a leveling off in ice extent. However, making use of the Community Earth System large ensemble (CESM-LE) and the CESM medium ensemble (single model ensembles), Jahn et al.[79] find that natural variability alone leads to an uncertainly in the timing of seasonally ice-free conditions of about two decades, while the uncertainly due to the emissions scenario (RCP4.5 versus RCP8.5) adds another five years. Nevertheless, in the RCP8.5 scenario, ice-free Septembers are the norm after 2060 while they are the exception in the RCP4.5 scenario.

A recurring theme regarding the trajectory to a seasonally ice-free Arctic Ocean is the idea of a "tipping point"—some critical value of ice thickness or greenhouse gas level that once passed, results in a very rapid loss of the remaining summer ice cover. Concern grew following the study by Holland et al.[80], which looked at projections of sea ice extent from a series of ensemble members generated by the NCAR Community System Model (CSM). In some of the runs, they found that as the climate warmed and the spring sea-ice cover thinned in response to rising greenhouse-gas levels, a strong kick from natural climate variability could induce a reduction in sea-ice extent sufficiently large enough to set the albedo feedback process into high gear. As a result, the path of a general downward trend in extent was interrupted by sudden plunges spanning a decade or more. Concern that a tipping point might be near (perhaps overstated by the media) grew after September 2007, which saw a then-record low extent over the period of satellite observations (23% below the previous record set in 2005), which as discussed earlier reflects the combined effects of several decades of sea-ice thinning and a highly unusual summer weather pattern.

However, subsequent work has shown that while there may well be sudden plunges in extent, there probably is no tipping point. As argued by Tietsche[81] on the basis of a series of idealized climate model experiments, autumn and winter heat loss acts as a strong negative (stabilizing) feedback. If an anomalous forcing leads to a large negative anomaly in September ice extent, there will also be large oceanic heat losses in autumn and winter from open water areas that in turn fosters a large production of new ice. The stabilizing effect of winter heat loss finds observational support in observed year-to-year changes in September sea ice extent. Years which have exhibited a strong negative change compared to the previous year (e.g., 2006 to 2007, 2011 to 2012) have been followed the next year by a positive change (and vice versa)[15,82] (Fig. 6).

The Antarctic enigma

In sharp contrast to the Arctic, sea ice extent in the Antarctic, for the year as a whole, has shown a weak but statistically significant upward trend over the period of satellite observations.[83–86] This trend reflects largely offsetting contributions of increasing extent over the Ross Sea and decreasing extent over the Amundsen–Bellingshausen Sea.[86,87] Recent years have seen particularly large variability with record high seasonal maxima in extent followed by record low maxima.

Most climate models project that the loss of Antarctic sea ice through the 21st century will not be as pronounced as in the Arctic. One of the reasons for this is that the strong circumpolar Antarctic current tends to limit oceanic heat transport into high southern latitudes. The atmospheric circulation, while quite variable, also tends to be more zonal than in the North Polar Region, meaning less pronounced excursions of warm air into the region. Katabatic off-shore winds can also open up coastal polynyas and push ice away from the coast. Nevertheless, hindcasts from most of the current generation of climate models simulate decreasing extent over the period of observations.[88]

While a full explanation for this puzzling upward trend has remained elusive, changes in atmospheric circulation appear to have played a prominent role. Ice extent in the Ross Sea is positively correlated with the strength of the Amundsen Sea Low, and the low has generally deepened since 1979**.** Meehl et al.[89] link this deepening and an acceleration of the positive sea ice trend since about the year 2000 to a switch from the positive to the negative phase of the Interdecadal Pacific Oscillation. Others have looked at the issue in the framework of the Southern Annular Mode (SAM)[90] and effects of changing winds on seasonal expansion of the ice cover[91] and increasing sea ice volume.[92] Other factors put forward include increased ice-shelf melt.[93] There is some indication that the modern (since 1979) satellite-era positive trend and recently-observed large interannual variability are within the range of natural climate variability. For example, early (and piecemeal) satellite records from the Nimbus-1 platform show that the difference in the contrasting seasonal maxima observed in 1964 and 1966 encompass the range observed in the modern satellite era.[94]

The reason for the high variability superposed upon the upward trend is that, unlike the Arctic (especially in winter), Antarctic ice extent is not bounded by land and is hence free to vary in response to atmospheric and/or oceanic influences. As an extreme example, during 2016, after a series of record high seasonal maxima, extent fell to record low, most pronounced in the Weddell and Ross Seas. Turner et al.[95] attribute this event to a very deep Amundsen Sea Low.

Conclusions

The downward trend in Arctic September sea ice extent is one of the most prominent signals of environmental change on the planet. The drivers of this trend, the variability around it, and predictability of ice conditions, have been addressed in hundreds of studies, and interest shows no signs of waning. There has been equal interest in the emerging environmental and human impacts of sea ice loss.[96] Via feedback processes, sea ice loss plays an important role in Arctic amplification—the observed outsized rise in near surface air temperatures over the Arctic compared to the rise for the globe as a whole.[97] There is heated debate over the question of whether Arctic amplification can have (or may already be having) significant impacts on the polar front jet stream and mid-latitude weather patterns.[98–101] Within the Arctic, sea ice loss has been linked to increased coastal erosion. This relates to the longer fetch of winds over open water that increases wave action as well as warming of the waters, fostering thermal erosion of costal bluffs "glued" together by permafrost.[102] There is also concern that warming can alter the character of precipitation, leading to more rain on snow events that can greatly interfere with the grazing of reindeer and other herbivores.[103] In turn, species such as polar bears walruses, belugas and narwhals are known to be sensitive to ice loss. [96]

Not all environmental impacts of ice loss are necessarily negative. For example, less sea ice means more light penetration into the water, which is linked to increased Arctic Ocean primary productivity.[104] This has led to more favorable conditions for zooplankton, leading to improved body condition of bowhead whales.[105] The warming Arctic Ocean has also favored poleward shifts in the range of commercially important fish species.[106]

Finally, as the ice retreats, the Arctic will become increasingly accessible for extraction of oil and natural gas, marine shipping of all kinds, and tourism. Conflicts may arise between stakeholders. Indeed, in many ways, issues surrounding the shrinking Arctic sea cover serve as the exemplar of the intertwining of climate change, environmental impacts, economics and geopolitics. The sharply contrasting behavior of the Antarctic sea ice cover remains to be completely resolved.

Acknowledgements

This study was supported by NSF Grants PLR 1603914 and OPP 1748953 and NOAA Grant 15OAR4310171.

Competing interests

The authors declare no competing interests

Figure legends

Figure 1. Seasonal cycles of Arctic and Antarctic sea extent, based on the satellite passive microwave record from 1979 through 2017. The heavy lines depict the daily averages while the shading depicts the bounds of the 10th and 90th percentile values.

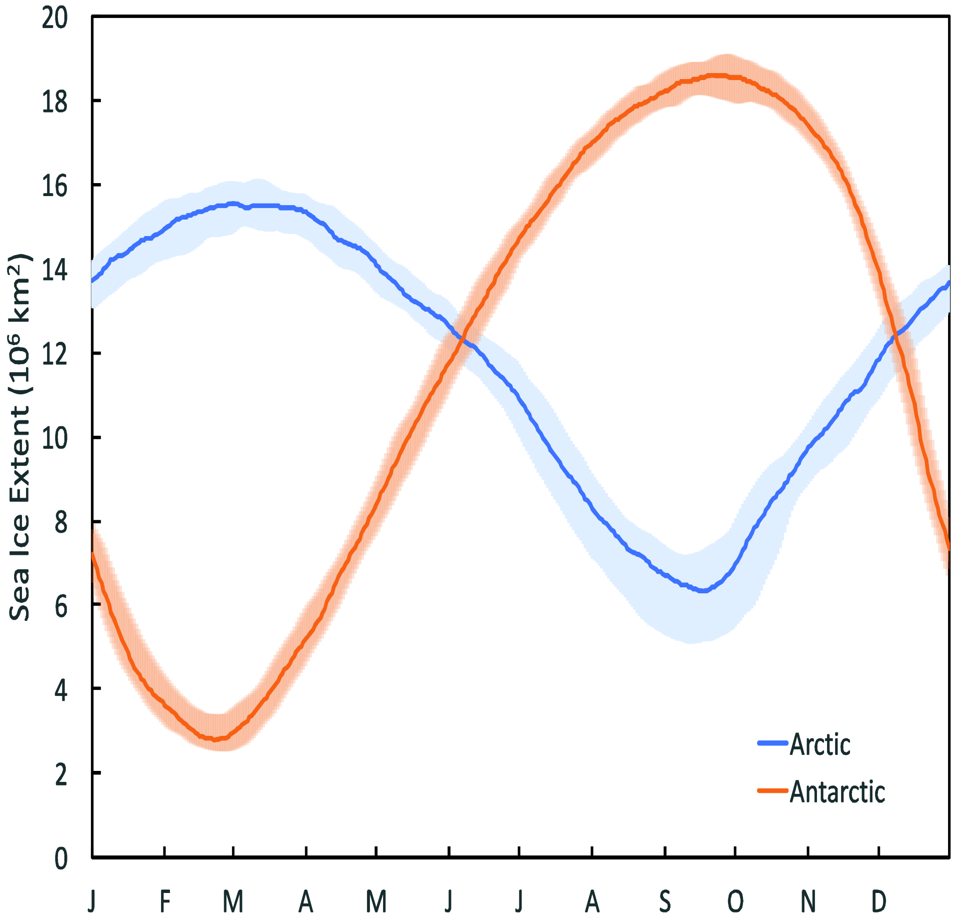


Figure 2. Average Arctic and Antarctic sea ice concentration for March and September, based on data from the satellite passive microwave record over the period 1979 through 2017.

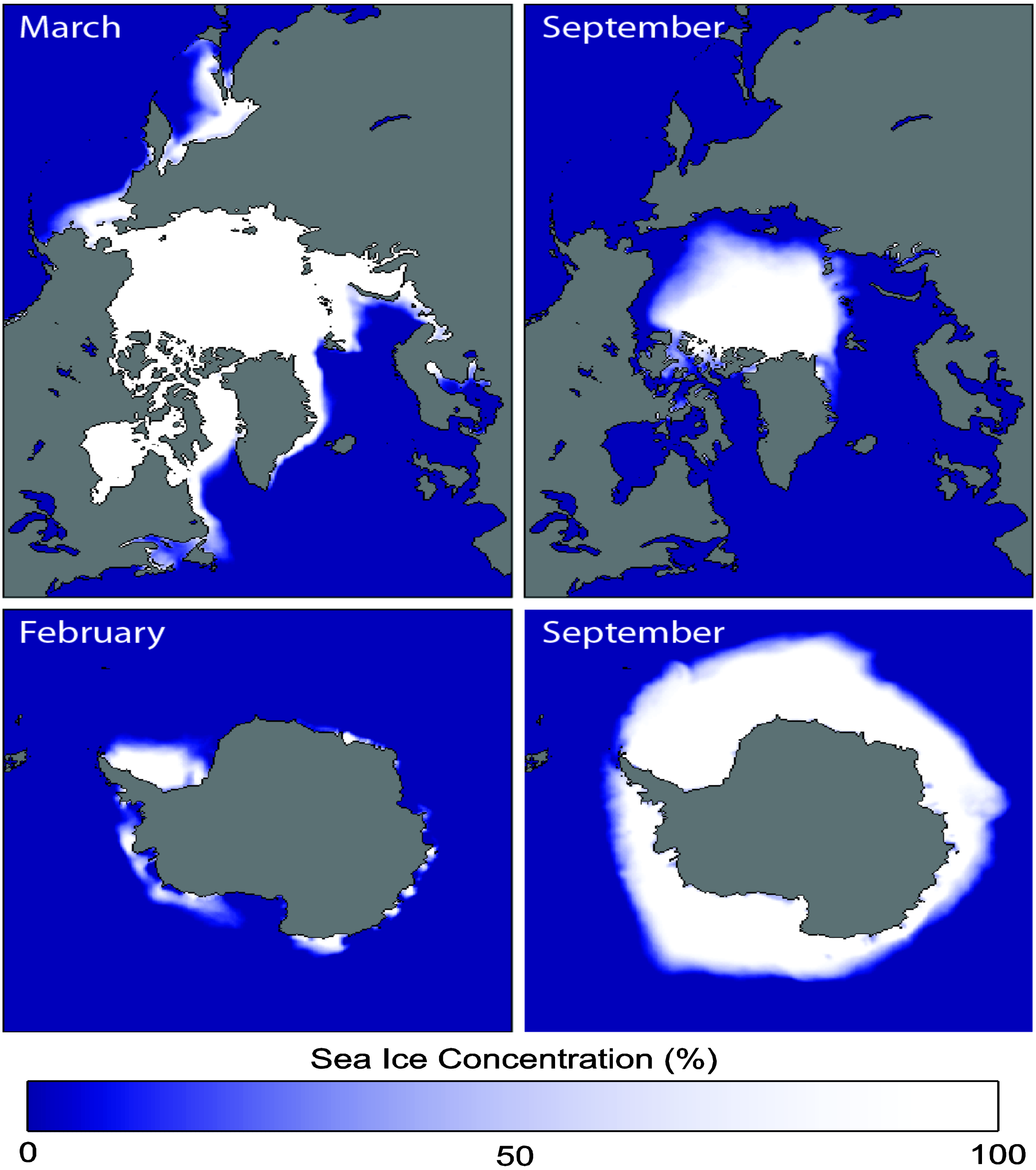


Figure 3. Average annual pattern of Arctic sea ice drift as shown by velocity vectors with overlay of annual mean sea level pressure.

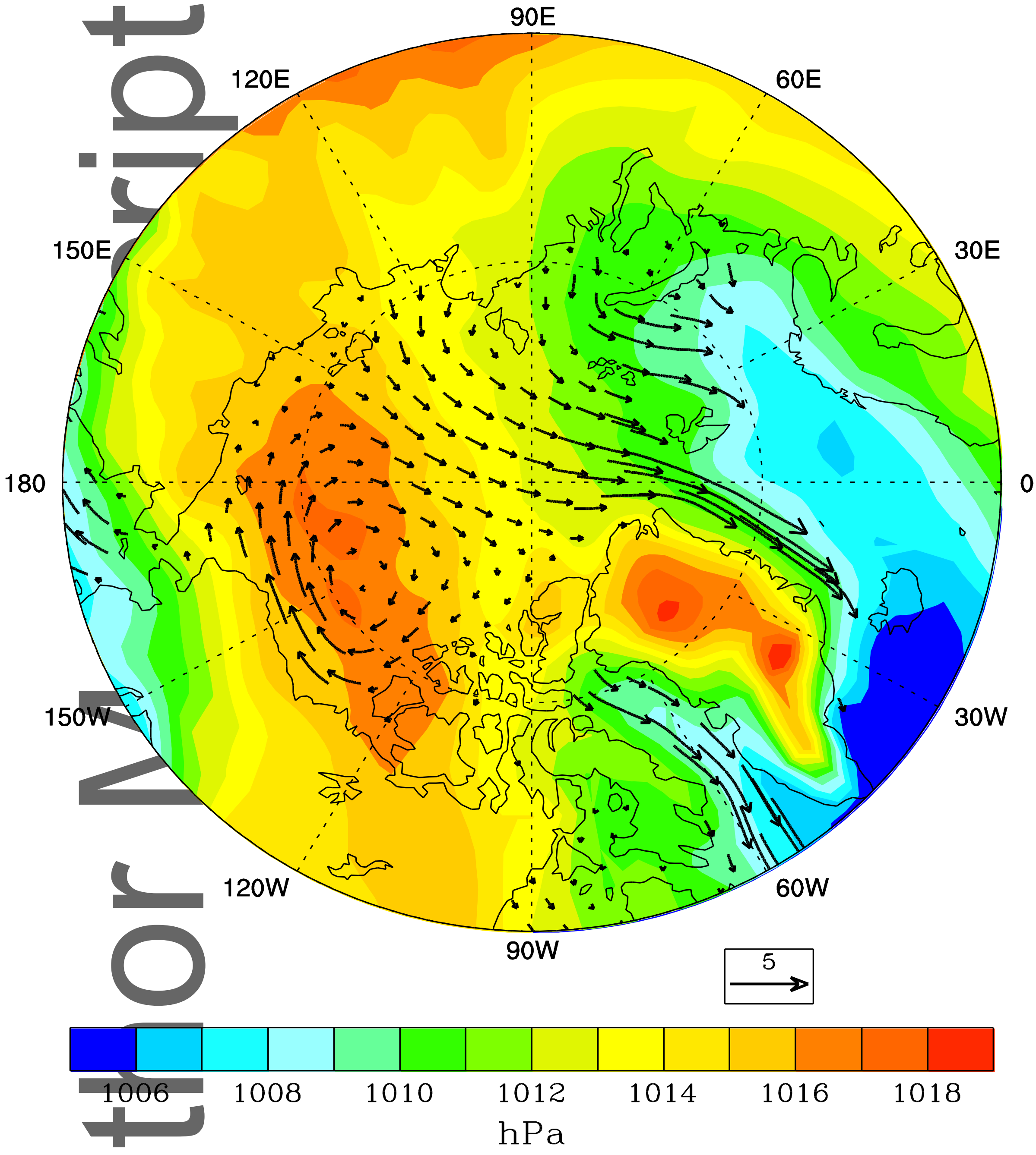


Figure 4. Time series and linear trends in Arctic sea extent for alternate months (January, March, May, July, September, November), based on the satellite passive microwave record over the period 1979 through 2017. The trend values are computed with respect to averages over the period 1981 through 2010.

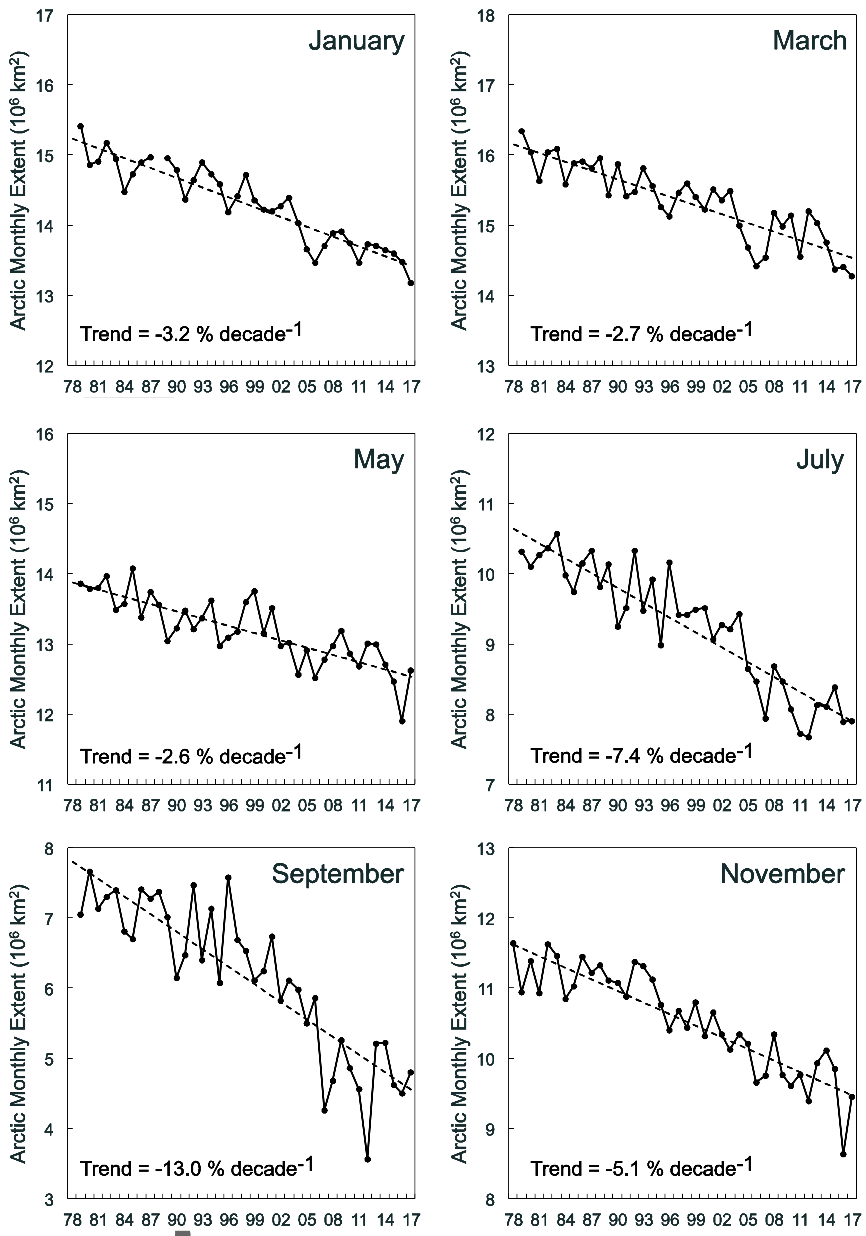


Figure 5. Spatial pattern of sea ice age classes for week 12 (end of March) of 2017 (top) and time series, 1984 through 2017 (bottom), based on an ice age tracking algorithm.

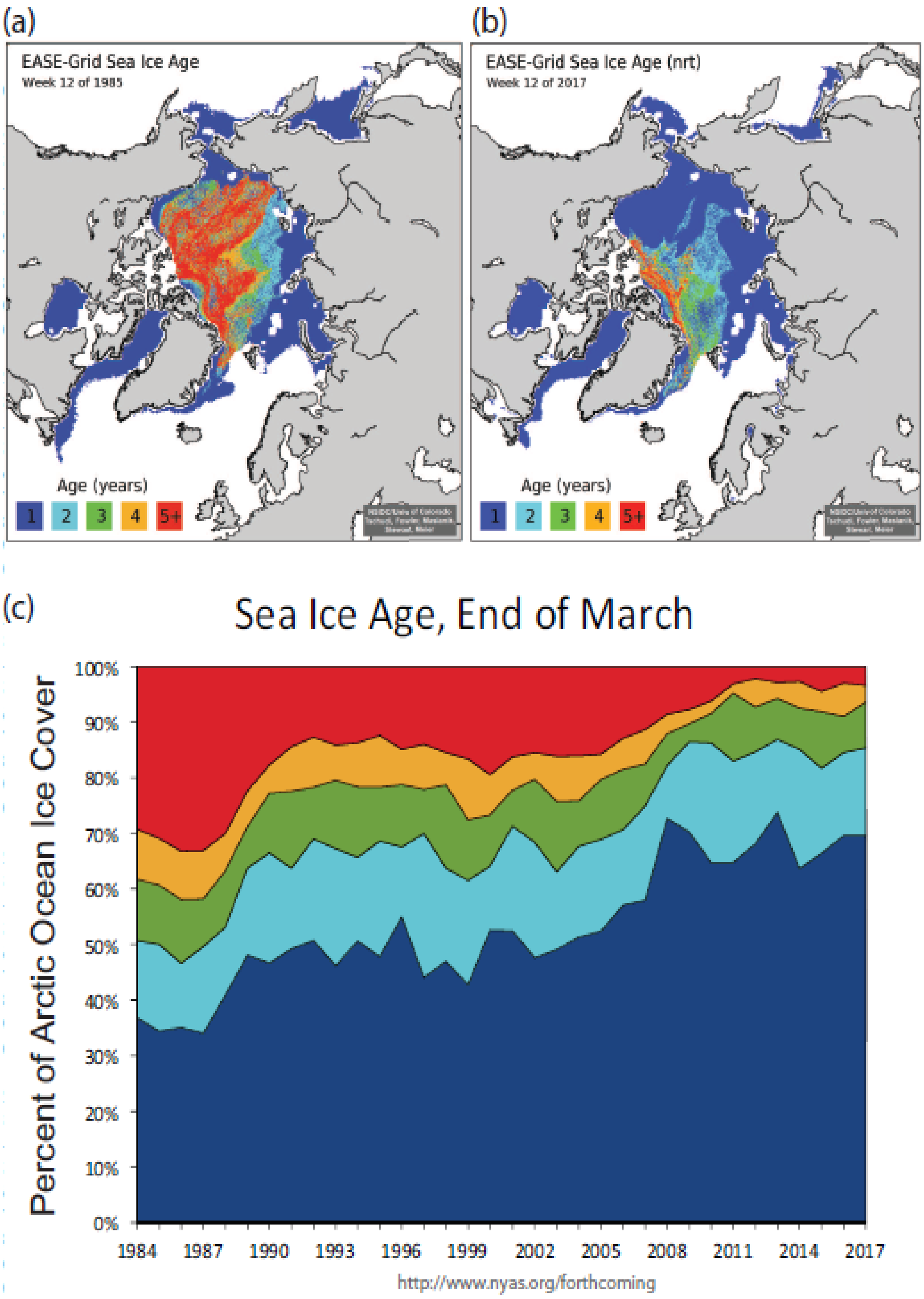


Figure 6. Departures of September sea ice extent from the linear trend line, based on the satellite passive microwave record from 1979 through 2017.

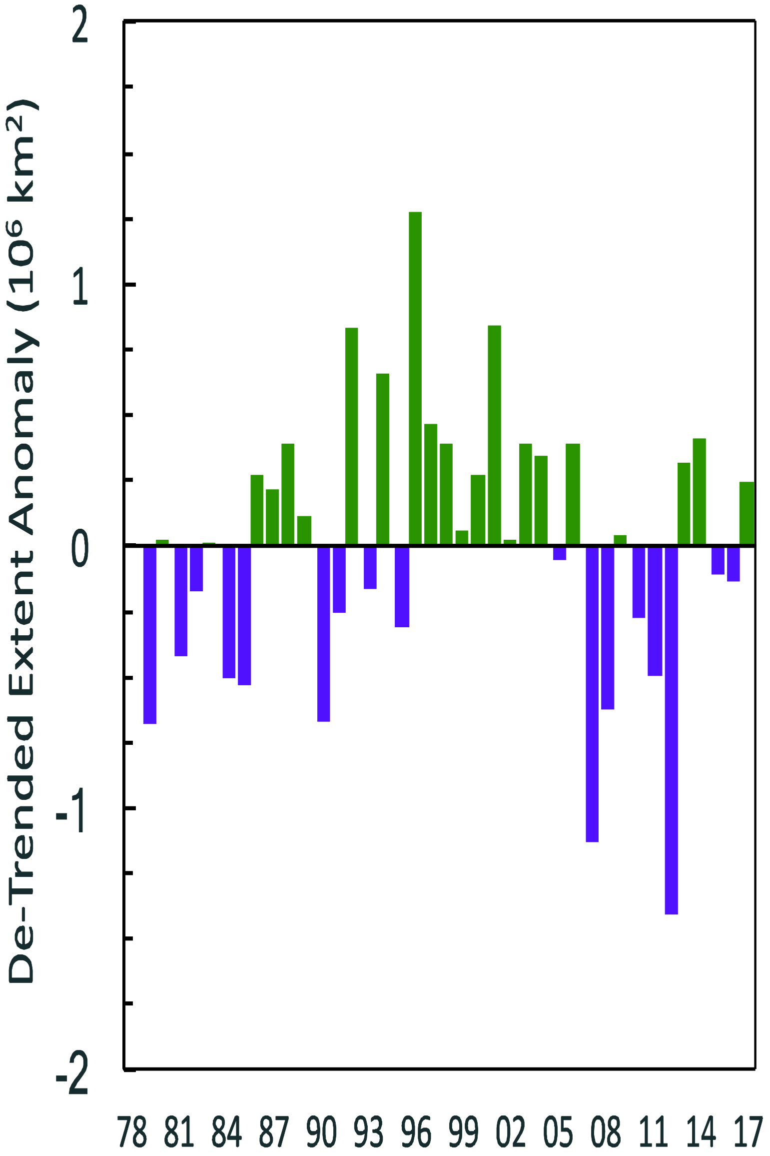


Figure 7. Sea level pressure anomalies averaged for June through August, 2007 (a) along with average sea ice extent for September 2007 (b). The sea level pressure anomalies are computed with respect to averages over the period 1981 through 2010. The purple line on the sea ice map shows the median September extent as assessed over the period 1981 through 2010.

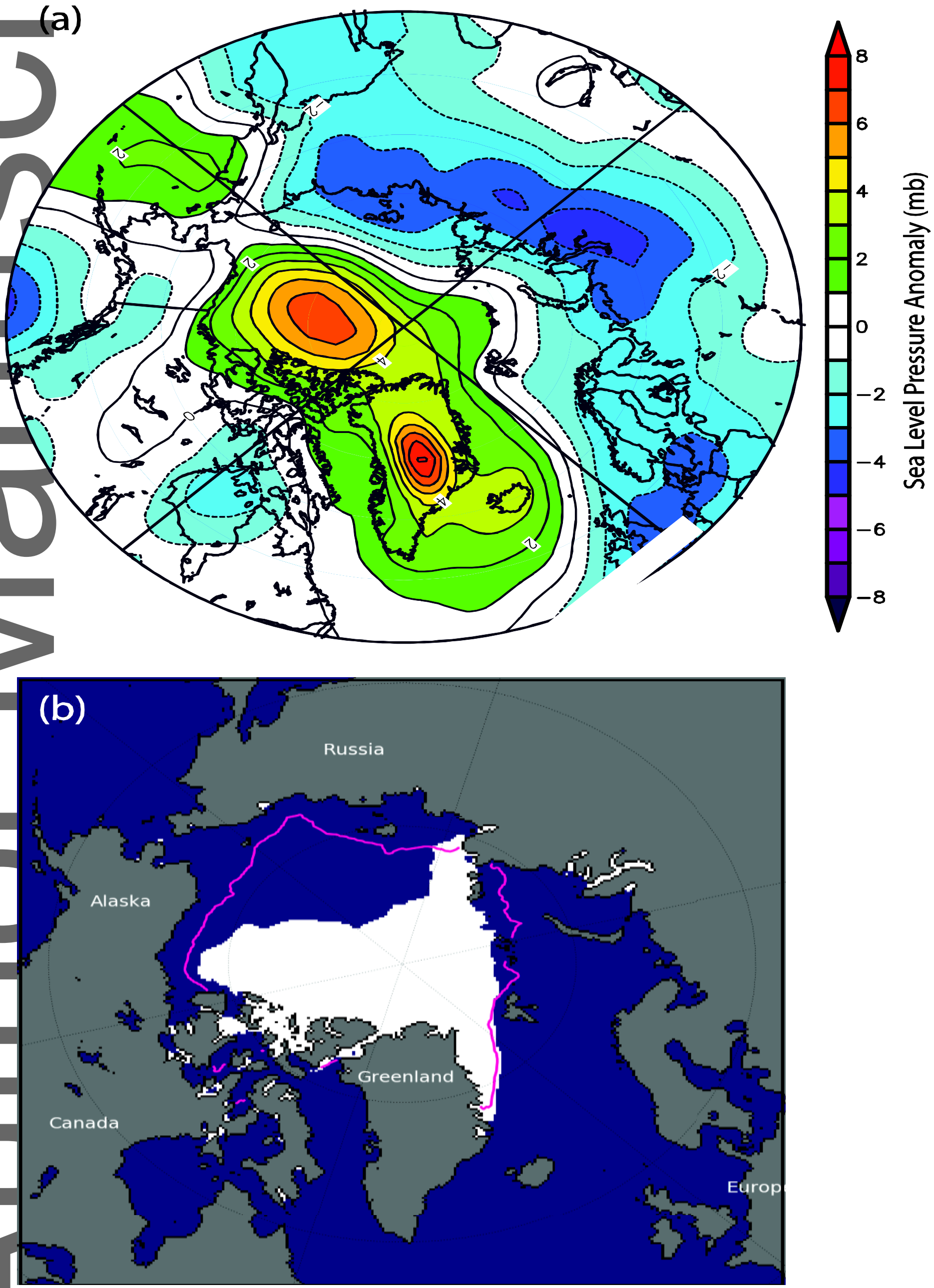
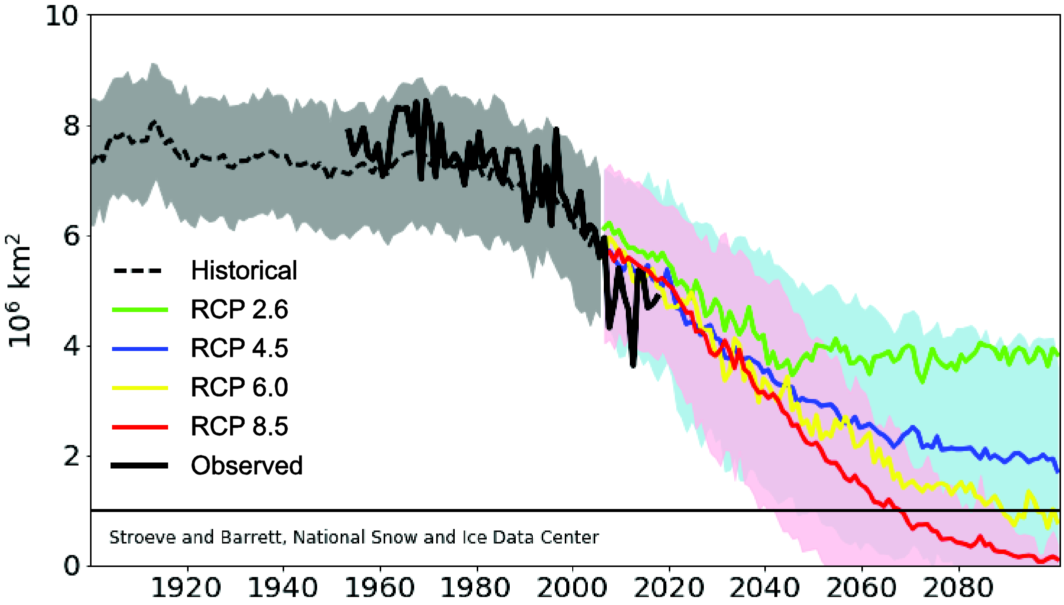


Figure 8. Hindcasts and projections of September Arctic sea ice extent from models participating in the IPCC 5th Assessment Report for different Representative Concentration Pathways (RCPs) along with observations. For the hindcasts, the multi-model average is shown by the dotted line, with the spread between the models indicated by gray shading. For the projections, the multi-model averages are shown by the bold colored lines, with the spread between the models shown by the shading. Observed ice extent is indicated by the thick black line.



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