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Arctic Sea Ice Decline

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1. Introduction

The Arctic is currently undergoing rapid environmental changes (ACIA, 2005; IPCC, 2007). One of the most striking of these changes is the decline in the floating sea ice cover. Sea ice is frozen sea water that forms in winter as temperatures drop and darkness sets over the northern high latitudes. At its winter maximum, roughly 14 to 16 million km^2 of the Northern Hemisphere ocean surface is covered by sea ice, extending as far south as Newfoundland, Canada (at 50^o latitude) along the eastern coast of Canada and as far south as Bohai Bay, China (at 38^o latitude) on the Eurasian side. During summer as temperatures warm, the ice cover shrinks to about half its winter size by September, covering on average 6 million km^2 (Figure 1).

Arctic sea ice is an important regulator of the exchange of heat and moisture between the atmosphere and the ocean. The presence of the sea ice cover insulates the relatively warm ocean from the colder atmosphere and because of its high reflectivity, its presence helps to keep the northern high latitudes cool by reflecting a large portion of the sun's energy back to space. Sea ice also exerts a strong influence on global atmospheric and oceanic circulation. Because of the Earth's orientation relative to the sun, the equator receives more incoming solar radiation than the poles. The inequality in the amount of solar radiation received gives rise to a temperature gradient that drives the circulation of air in the atmosphere that transports heat from the tropics to the poles.

During winter, there is little solar energy and sea ice acts as a very effective insulator, preventing heat in the Arctic Ocean from warming the lower atmosphere. During early spring, as the sun rises in the Arctic, but temperatures remain cold, the snow-covered sea ice remains frozen and may reflect more than 80 percent of the sun's energy back to space. As temperatures rise through the spring and summer, the snow melts, bare ice is exposed and melt ponds form, allowing for more of the sun's energy to be absorbed by the surface. However, even under these melt conditions the ice surface usually reflects 50% or more of the sun's energy. Additionally, since most of the solar energy absorbed by the ice in summer is used to melt ice, near surface air temperatures stay fixed near the freezing point. As the ice melts out completely in summer, the exposed darker ocean surface absorbs roughly 90 percent of the sun's incoming energy. This causes the oceans to warm up. Before the ice can once again reform in autumn, the ocean must first release the heat gained in summer back to the atmosphere, warming the lower troposphere.

The strong seasonal cycle of the Arctic sea ice cover not only affects our weather patterns, it also affects human activities and biological habitats. For example, hunters in the Arctic depend on the ice cover as a platform to hunt for Arctic mammals, such as seals, whales, walruses and polar bears. These species themselves depend on sea ice for their habitat, using the ice as places to breed, feed and hunt for food. The timing of the phytoplankton bloom, which supplies energy to the entire Arctic ecosystem, is also regulated by the timing of the ice retreat. Shipping companies are starting to take advantage of less sea ice in the summer to ship materials through the Arctic and the potential for extraction of natural resources, such as oil and natural gas, is also drawing increasing attention.

Over the past few decades, the Arctic has warmed at about twice the rate as the rest of the planet. As a result, significant changes are happening in the Arctic sea ice cover, with potentially large implications not only regionally but also for the global climate. This chapter discusses recent Arctic sea ice changes, the factors responsible for these changes, what climate models project for the future, and our current understanding of the climatic impacts of continued sea ice loss.

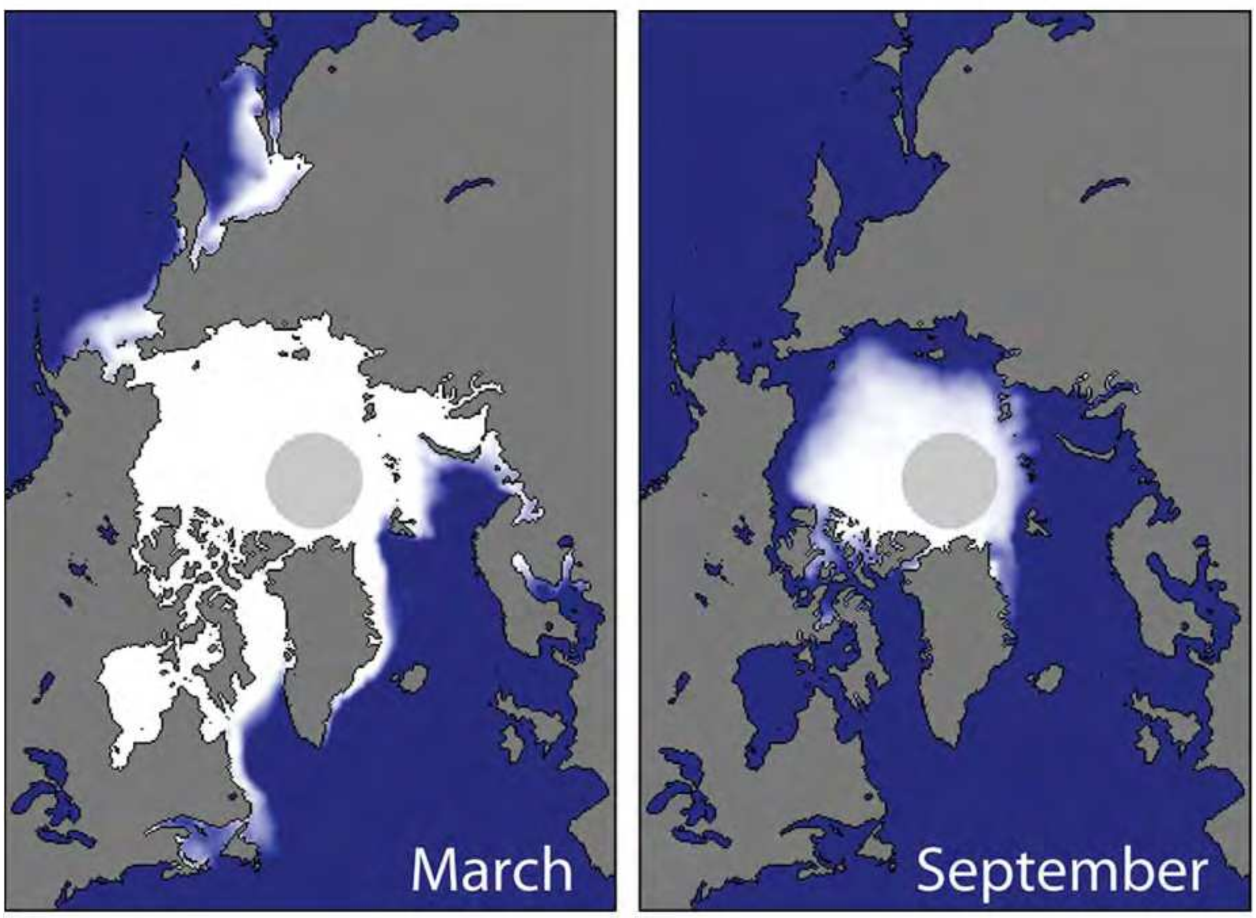


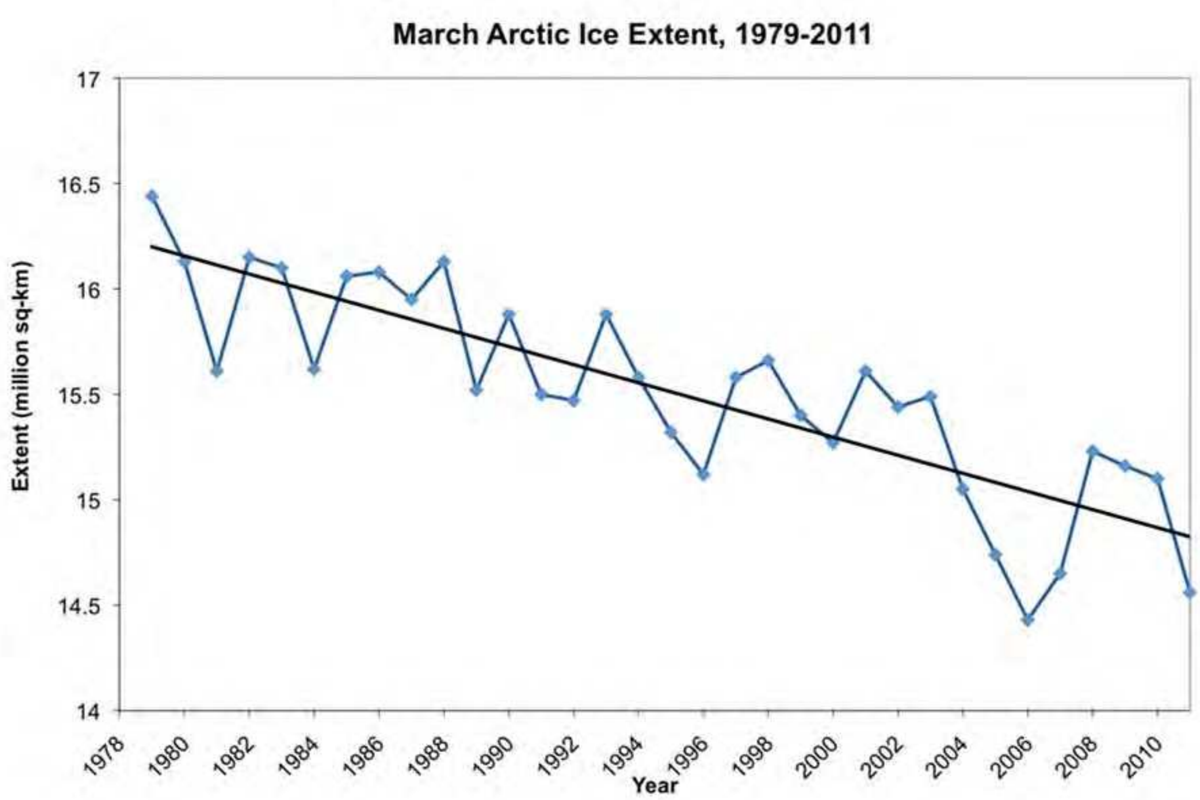
Fig. 1. March (left) and September (right) mean seasonal ice cover. The area in grey near the pole is the area not seen by the satellite sensor.

2. Recent changes in the Arctic sea ice cover

2.1 Ice extent

Before the satellite era, it was not easy to obtain reliable measurements of Arctic sea ice. The Arctic is remote and can be an inhospitable place. Early ship, submarine and aircraft observations provide some local information, but it wasn't until the late 1960s/early 1970s that satellites were able to provide the first broad look at changes in the sea ice cover. The modern passive microwave satellite data record further allowed for monitoring of ice conditions regardless of sunlight or cloud cover. Starting with the launch of NASA's Scanning Multichannel Microwave Radiometer (SMMR) satellite in October 1978, and continuing on with a series of Special Sensor Microwave/Imager (SSM/I) instruments on the Defense Meteorological Satellite Program (DMSP) satellites, scientists now have a consistent time-series of sea ice changes that spans nearly 34 years.

Analysis of this data record shows that since the late 1970s, the amount of sea ice covering the ocean has declined during all calendar months (Serreze et al., 2007). The trends are smallest in winter and strongest in late summer and early autumn (Figure 2). However, in recent years, the trend in the end-of-summer ice extent has accelerated. Every year since 2002 has been characterized by extreme September ice extent minima (Stroeve et al., 2008; Comiso et al., 2008; Stroeve et al., 2011a). Through 2001, the linear trend in September ice extent over the satellite record stood at -7.0% per decade. By 2010, it increased to -12.4% per decade. Yet another record or near-record low is expected for September 2011. This represents a ~40% reduction in the surface area of the Arctic Ocean covered by sea ice.



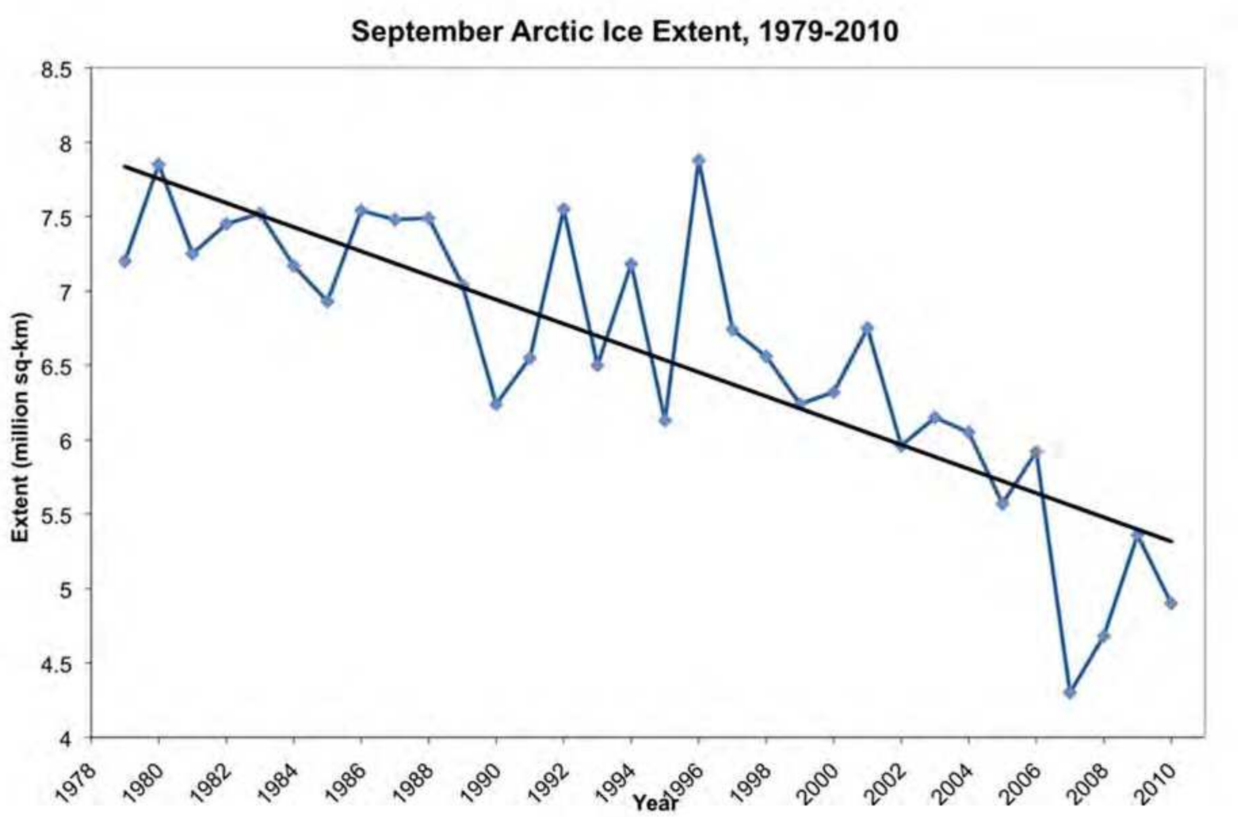


Fig. 2. Monthly mean March (top) and September (bottom) sea ice extent from 1979 through present derived from the passive microwave satellite data record and using the NASA Team sea ice algorithm.

During the 1980s and the 1990s, a low summer sea ice year would often be followed the next year by higher summer extents. In addition, the Arctic-wide low sea ice anomalies tended to be characterized by less ice the Eurasian side (i.e. Laptev or E. Siberian seas) with average or anomalously more sea ice on the Alaskan side (i.e. Chukchi and Beaufort seas) or vice versa. However, ice losses during the past decade have been characterized by pronounced sea ice retreat from both the Alaska and Siberia shores (Figure 3). The last several years have also seen opening up of the northern shipping routes. The last four summers saw opening of the Northern Sea Route, a shipping route that runs along the Russian Arctic coast from Murmansk on the Barents Sea to the Bering Strait and the Far East. Additionally, the Northwest Passage southern route, a waterway amidst the Canadian Arctic Archipelago was open the past five summers.

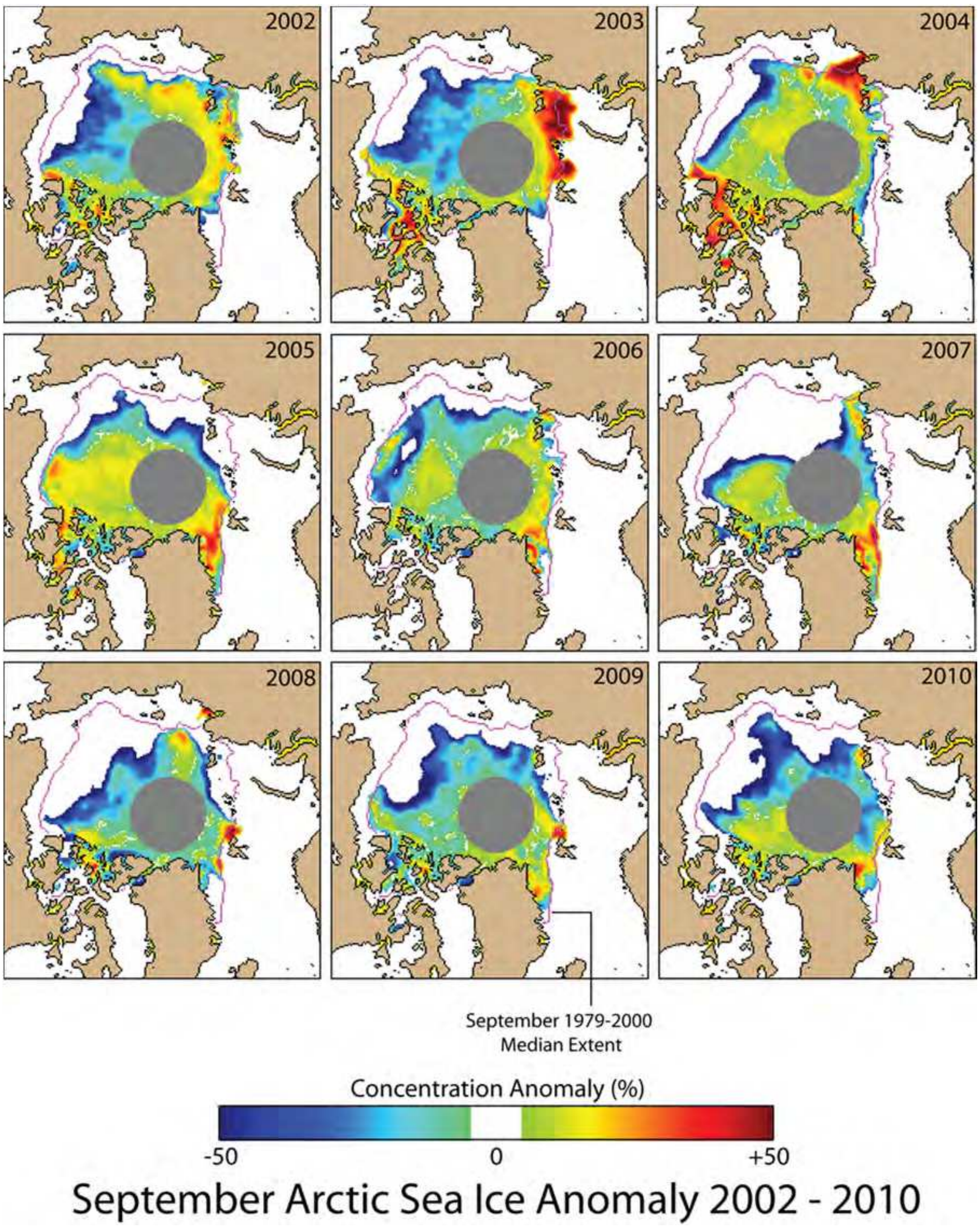


Fig. 3. Sea ice extent anomaly maps, 2002-2010: Sea ice conditions for the month of September, 2002 through 2010, derived from the NSIDC Sea Ice Index. Each image shows the concentration anomaly (see color key) and the 1979-2000 mean September ice edge (pink line). Nearly every year, the ice edge is well north of its mean position off the coasts of Alaska and Siberia. Image provided by National Snow and Ice Data Center, University of Colorado, Boulder.

2.2 Ice thickness

At the same time that the spatial coverage of the summer ice cover is shrinking, the ice cover is also thinning. Comparisons between early upward looking sonar aboard submarines (1958-1976) and those from 1993 to 1997 suggested a reduction of 1.3 m in the mean late summer ice thickness over much of the central Arctic Ocean [(Rothrock et al., 1999)]. However, sparse sampling has complicated the interpretation of wide-spread changes in the Arctic ice thickness. Rothrock et al. [(2003)] further analyzed the submarine data in conjunction with model simulations and found that there was a modest recovery in ice thickness after 1996. *In situ* measurements of thickness have been collected during short field experiments at scattered locations. These measurements have proven valuable for validation of submarine and satellite data, but do not provide useful information on the Arctic-wide sea ice thickness.

In recent years, satellites have allowed for further assessment of sea ice thickness changes. Giles et al. [(2008)] and Laxon et al. [(2003)] demonstrate the ability to derive ice thickness estimates from satellite radar altimetry (i.e., from the European Space Agency's (ESA) ERS1/2, Envisat) to an accuracy of 4 to 6 cm, excluding regions thin ice (below 0.5 m). These satellites have a latitudinal limit of 81.5°N but have proven valuable in assessing changes in ice thickness, with high correlations between derived ice thickness fields and submarine estimates of ice thickness (r=0.99) [(Laxon et al., 2003)]. Thickness estimates based on measurements taken by NASA's Ice, Cloud and land Elevation Satellite (ICESat) laser altimeter launched in January 2003 provide a further update on thickness changes during the time when large changes in the summer ice cover have occurred (satellite mission ended In 2009). Using this data in conjunction with the submarine thickness record, Kwok and Rothrock [(2009)] determined that the Arctic mean ice thickness declined from 3.64 meters in 1980 to 1.89 meters in 2008, or a total decline of 1.75 meters. CryoSat-2 is another radar altimeter instrument that was launched in April 2010 by ESA, but covers higher latitudes than the earlier radar altimeter satellites and has a 250 m resolution along the track. ICESat-2 is planned for launch early 2016. Together CryoSat-2 and ICESat-2 are expected to achieve improved accuracy in sea ice thickness retrievals over a broad spatial scale.

2.3 Ice age

The large decreases in summer sea ice extent in recent years [(e.g., Comiso et al., 2008; Stroeve et al., 2008; Stroeve et al., 2005)] further manifest a fundamental transition from a largely perennial ice cover where ice persists from year to year, to a seasonal coverage with substantial open water during summer [(e.g., Kwok, 2007; Maslanik et al., 2007a; Kwok and Cunningham, 2010)]. Using satellite-derived ice motion fields, the age of an individual ice parcel can be tracked by treating each grid cell that contains ice as an independent Lagrangian particle and advecting the particles at weekly time steps [(Fowler et al., 2004)]. In cases where particles of different ages fall within a single grid cell, the age of the grid cell is assigned to the oldest particle. These fields reveal a dramatic decline during the past 30 years in the Arctic's multiyear ice cover [(Figure 4)]. The fraction of total ice extent made up of multiyear ice in March decreased from about 75% in the mid-1980s to 45% in 2011, while the proportion of the oldest ice (i.e. ice 5 years or older) declined from 50% of the multiyear ice pack to 10% [(Maslanik et al., 2011)]. Reductions in old ice now extend into the central Arctic Ocean and adjacent to the Canadian Archipelago, areas where the ice cover was relatively stable prior to 2007 and where long-term survival of sea ice through summer is considered to be most likely.

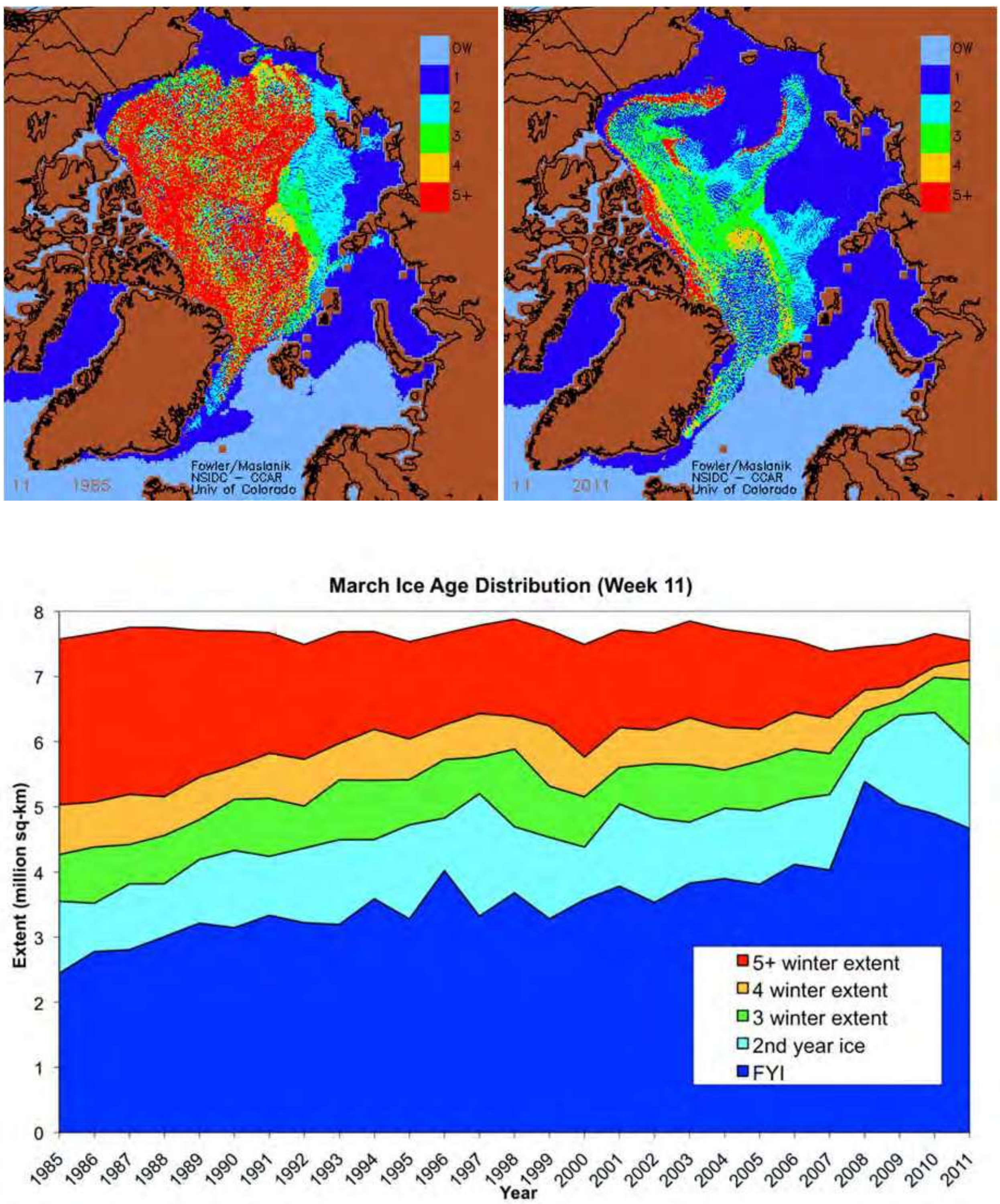


Fig. 4. Spatial distribution of ice of different age classes during March (week 11) in 1985 (top, left) and 2011 (top, right). Bottom figure shows the total extent of ice of different age classes for the Arctic Ocean domain. Data from C. Fowler and J. Maslanik, CCAR, University of Colorado.

Mapping the age of the sea ice not only provides a measure of how much the ice cover has transitioned from a largely perennial ice cover, where ice persists from year to year, to more of a seasonal coverage, it also provides an additional indication of sea ice thickness. Using February and March ICESat-derived thickness fields for the years 2003 and 2006, Maslanik et al. [(2007)] calculated mean ice thickness as a function of ice age. This comparison suggested a nearly linear relationship between age and thickness, with a 0.19 m yr^{-1} increase in thickness with age up to thickness values about 3 m, the approximate limit for thermodynamic ice growth. Thus, substituting these mean thicknesses for age at each grid cell provides an approximation of thickness, with the advantage of offering extended time coverage versus the ICESat data alone. Maslanik et al. [(2007)] suggested that using the ice age as a proxy for thickness shows that the Arctic has experienced significant thinning between the 1980s and 2006, corresponding to a ~40% reduction in ice volume.

3. Factors behind the sea ice decline

The decline in Arctic sea ice can be best explained from a combination of natural climate variability, such as variability in air temperature, atmospheric and oceanic circulation, and from external forcing due to rising concentrations of atmospheric greenhouse gases (GHGs) [(e.g. Serreze et al., 2007; Kay et al., 2011)]. Global climate models have long predicted the rise in atmospheric air temperatures as GHG concentrations in the atmosphere increase [(e.g. IPCC, 2007 and references therein)]. In the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), hindcast simulations from the coupled GCMs that incorporate the observed record of GHGs show that the increase in global temperature results in a decline in the Arctic sea ice cover. However, while these model simulations were found to reasonably simulate the seasonal cycle in the sea ice cover [(e.g. Zhang and Walsh, 2006)], Stroeve et al. [(2007)] found that the observed winter (March) and summer (September) rates of decline were triple the respective model ensemble means, and for September the observed rate of decline was larger than all of the individual model runs. While the qualitative agreement between the GCM simulations and the observations provides evidence for a role of GHG forcing on the observed decline, the disagreement on the rate of decline could indicate a substantial natural variability component or an underestimation of the sea ice sensitivity in the models.

3.1 Changes in atmospheric circulation

An important contribution towards the recent decline in extent and thickness of the sea ice cover came from an atmospheric shift in the late 1980s, early 1990s, when the Arctic Oscillation (AO), also referred to as the Northern Annual Mode (NAM), was predominately in a positive phase [(Rigor and Wallace, 2004)]. The AO is defined as the leading stationary mode of variability in the northern hemisphere sea level pressure (SLP) field based on Empirical Orthogonal Function (EOF) analysis. As such, the AO can be interpreted as an exchange of atmospheric mass between the Arctic and the mid-latitudes [(Thompson and Wallace, 1998)]. When the AO is in its positive phase, SLP over the Icelandic region and extending into the Arctic is anomalously low, promoting a cyclonic (counter-clockwise) sea ice circulation anomaly. This results in decreased ice transport from the Beaufort Sea westward across the date line into the Chukchi Sea, increased ice transport out of the Arctic Ocean through Fram Strait, and increased transport of ice away from the Siberian coast, leaving open water areas that foster new ice formation [(Rigor et al., 2002)]. By promoting more thin ice in spring, the positive AO sets the stage for negative anomalies in summer ice extent in the Siberian Arctic. It is widely believed that the late 1980s through the mid 1990s positive winter AO state led to significant export of old, thick ice out of the Arctic via Fram Strait, leaving behind thinner ice that is more vulnerable to summer melt [(e.g. Rigor and Wallace, 2004; Lindsay and Zhang, 2005; Maslanik et al., 2007; Nghiem et al., 2007)].

Another key driver for recent record low summer ice extents has been persistence of a summer atmospheric circulation pattern defined by anomalously high SLP over the Beaufort Sea and Canada Basin and unusually low SLP over eastern Siberia, termed the Arctic Dipole Anomaly (DA) [(Wu et al., 2006; Overland et al., 2008; Wang et al., 2009)]. This circulation pattern leads to warm southerly winds in the Chukchi and East Siberian seas, favoring melt and transporting ice northwards towards the pole. In 2007 the DA was particularly well developed throughout the entire summer [(Figure 5]), resulting in very strong southerly winds that transported ice away from the coasts of Siberia and Alaska, as well as enhanced transport of ice out of the Arctic Ocean and into the North Atlantic through Fram Strait [(Wang et al., 2009)]. Another feature of the anomalously high pressure over the Beaufort Sea in 2007 was unusually clear skies that enhanced surface and basal melt [(Kay et al., 2008)]. While the DA has not been as strong or persistent in the summers following 2007, it has been a common feature of the summer circulation pattern [(Stroeve et al., 2011a)].

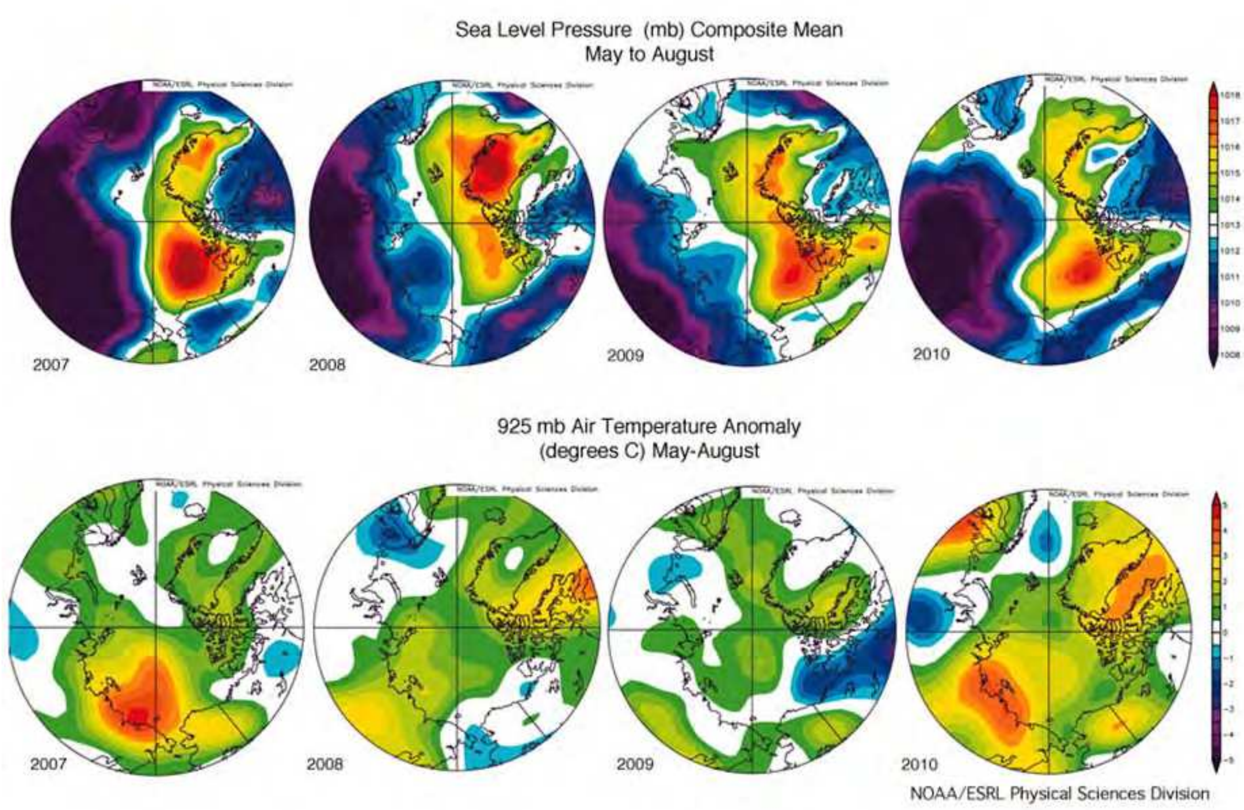


Fig. 5. Composite mean sea level pressure from May through August for 2007 through 2010 (top) and corresponding 925 hPa air temperature anomaly (bottom). Data are from the NOAA/ESRL Physical Sciences Division. Figure from Stroeve et al. (2011a).

3.2 A warming climate

Another important factor behind the decline in the sea ice cover is that Arctic air temperatures are rising [(e.g. ACIA, 2005 and references therein)]. Figure 6 shows temperature anomalies by year and month at the 925 hPa level for the Arctic Ocean domain from JRA-25 atmospheric reanalysis, a product of the Japan Meteorological Agency [(Onogi et al., 2007]). Anomalies are computed with respect to means for the period 1979-2010. In the earlier part of the record, it was common for an anomalously warm summer, contributing to a negative September ice extent anomaly, to be followed by an anomalously cold winter or summer, helping to bring about recover in the ice cover. However, since about 2000, positive air temperature anomalies dominate all months, making it more difficult for the ice cover to rebound from an anomalously low sea ice year. The warmer air temperatures during the past decade have been linked to increased concentrations of black carbon aerosols [(e.g. Shindell and Faluvegi, 2009]), increased spring cloud cover that leads to increased downward longwave radiation at the surface [(Francis and Hunter, 2006]), changes in atmospheric circulation patterns that transports warm air into the Arctic [(*Yang et al*., 2010]), and changes in oceanic heat transport [(Polykov et al., 2005; Shimada et al., 2006]). Other factors include the loss of the ice cover itself as well as increases in atmospheric GHGs (discussed shortly).

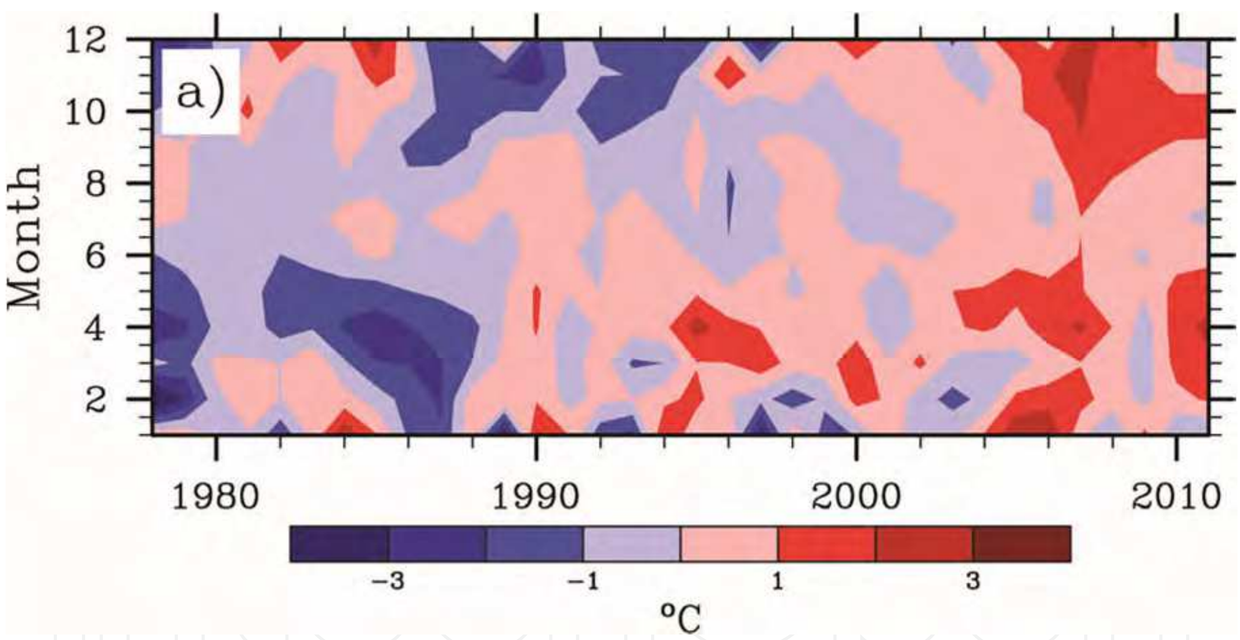


Fig. 6. Near surface air temperature anomalies (925 hPa) for all regions north of 60°N by year (x-axis) and by month (y-axis). Temperature anomalies are derived relative to the 1979 to 2010 mean.

Warmer spring temperatures have led to earlier melt onset in recent years [(e.g. Markus et al., 2009; Belchansky et al., 2004]). The earlier the ice begins to melt, the earlier the albedo drops, leading to increased absorption of solar radiation that further melts the ice and helps to cause open water areas to develop earlier during summer. These expanding open water areas absorb even more of the sun's energy, leading to enhanced basal and lateral melt. Deposition of black carbon and other impurities on the ice cover further increases the absorption of solar radiation, leading to enhanced ice melt.

Warmer autumn temperatures have correspondingly led to later autumn freeze-up and a lengthening of the melt season by 20 days over the last three decades [(Markus et al., 2009]). Temperature anomalies are especially strong in October, a month after the seasonal sea ice minimum. This has been linked to more open water areas in September, leading to strong transfer of heat from the ocean mixed layer (the top 50 meters of the ocean) to the atmosphere as the ocean refreezes [(e.g. Serreze et al., 2009; Screen and Simmonds, 2010a, 2010b; Serreze et al., 2011]). Because it takes time for the ocean to lose its mixed layer sensible heat, the ice that grows will not be as thick as it used to be in spring. This represents a feedback in that the thinner ice will more readily melt out the next summer. Other factors towards warmer autumn temperatures include increased horizontal atmospheric heat flux convergence [(e.g. Yang et al., 2010]), increased ocean heat flux convergence [(Chylek et al., 2009]) and changes in cloud cover and atmospheric water vapor that augment the downwelling longwave radiation flux to the surface [(Francis and Hunter, 2008]).

3.3 Enhanced ice-albedo feedback

As mentioned in the introduction, snow-covered sea ice has a high albedo, reflecting much of the incoming sun's radiation back out to space. As the snow begins to melt, the bare ice is exposed which absorbs more of the sun's energy. During advanced melt, melt ponds and areas of dark open water (low albedo) form, which readily absorb solar radiation, fostering further ice melt. Without this "ice-albedo" feedback, the amplitude of the seasonal cycle in ice extent (the change from March through September) would be smaller than is observed.

The continued decline in the summer ice cover has in part been attributed to a growing importance of the ice-albedo feedback [(Perovich et al., 2007; Lindsay et al. 2005]). With thinner first-year ice replacing thick multiyear ice, dark open water areas form earlier in spring, leading to increased sensible heat content of the ocean mixed layer, fostering further melt [(Stroeve et al., 2011a]). The shift towards more first-year ice also has large implications for the amount of solar energy absorbed by the sea ice itself since multiyear ice tends to have a higher albedo than first-year ice [(Perovich et al., 2000]). This in turn affects the strength of the ice-albedo feedback and hence the sea ice and upper ocean energy balance. The growing albedo feedback appears to be especially strong in the Beaufort and Chukchi seas, such that it is now warm enough that multiyear ice drifting into the region tends to melt out [(Stroeve et al., 2011b; Maslanik et al., 2011, Kwok and Cunnigham, 2010]).

It has been thought that this feedback could lead to a "tipping point" where the Arctic reaches a point of no return making summer ice-free conditions inevitable and to some extent irreversible [(e.g. Holland et al., 2006; Lindsay and Zhang, 2005]). However, more recent model results indicate that such a tipping point is unlikely [(Amstrup et al., 2010; Tietsche et al., 2011]). After the additional heat in the ocean is dissipated in the autumn, the sea ice can grow rapidly under the cold atmosphere, and because ice growth is fastest when ice is thin and then slows as the ice thickens through the winter, the final spring thickness of seasonal ice is only slightly thinner than normal. This mitigates some of the effects of the ice-albedo feedback. Thus, if temperatures stabilize or decrease, the summer sea ice will quickly recover to an equilibrium state determined by the temperature. Another implication of this is that the sea ice decline may be interrupted by several-year periods of little decline or even short-term increases in extent due to natural variability in the climate system [(Kay et al., 2011]).

3.4 Warmer ocean temperatures

There is growing evidence that the waters of the Arctic are warming. Since the 1990s, there has been an overall increase in the temperature and transport of warm Atlantic water through Fram Strait [(Schauer et al., 2004; Polyakov et al., 2005; Dmitrenko et al., 2008]). However it is unclear how much of this heat can be brought to the surface to melt the ice cover. This is because the warm Atlantic water exists below the colder, fresher (less dense) Arctic surface water. A more recent study found that the Atlantic water flowing north into the Arctic Ocean is the warmest that it has been in at least 2,000 years [(Spielhagen et al., 2011]). This large heat input into the Arctic appears to have caused an enhanced heat flux to the surface, concurrent with the decreasing sea ice cover.

On the Pacific side of the Arctic there is also indication of warm water inflow that is capable of reaching the surface and melting the ice from below. Shimada et al. [(2006]) find increases in Pacific Surface Water temperature in the Arctic Ocean beginning in the late 1990s that appear to have helped melt ice in the Chukchi and Beaufort seas. Jackson et al. [(2010]) finds that near surface (20-25 m depth) ocean temperatures in the Canada Basin have increased and moved further northward between 1993 and 2007.

3.5 Atmospheric greenhouse gases

All models participating in the IPCC 2007 AR4 report show declining sea ice extent over the period of observations when forced with the observed record of atmospheric GHGs [(e.g. Stroeve et al., 2007; Bo et al., 2009; Zhang and Walsh, 2006; Overpeck, 2005]). This is not the case when the models are run using pre-industrial levels of atmospheric greenhouse gasses and provides strong evidence that GHGs are in part responsible for the observed decline. Stroeve et al. [(2007]) estimated that 47-57% of the decline from 1979-2006 could be explained by GHG-forcing assuming that the multi-model ensemble mean was an accurate representation of the forced change by GHGs. Min et al. [(2008]) examined the observed changes from 1953-2006 together with the AR4 models and concluded that since the 1990s there has been a detectable anthropogenic forcing on the sea ice trends. A more recent paper by Kay et al. [(2011]) analyzed the influence of anthropogenic forcing on the late 20th and early 21st century Arctic sea ice extent trends using the latest version of the Community Climate System Model version 4 (CCSM4). They concluded that the observed ice losses could not be explained by natural climate variability alone.

Another feature of the GCM simulations is that some of the models show that the decline becomes steeper with time, but not until much later into the 21st century [(e.g. Wang and Overland, 2009]). However, it appears that accelerated ice loss is already happening today. Stroeve et al. [(2011a]) argue that the recent steepening in the rate of decline of September ice extent points to a growing non-linear response to external climate forcing. This growing non-linear response is related to the following. First, because there is less sea ice in September, there is more open water in which new ice can form in winter. Since this ice is thinner than ice that has survived more than one melt season, the following spring ice cover is increasingly dominated by thinner ice that is more vulnerable to melting out in summer, especially when atmospheric forcing is conducive to ice loss [(e.g. Lindsay et al., 2009]). Second, the presence of more thin ice in spring, allows open water areas to develop earlier in the melt season, leading to increased importance of the ice-albedo feedback [(e.g. Stroeve et al., 2011a, 2011]), though to some degree mitigated by the more rapid autumn ice growth, as discussed above. During the record ice loss year of 2007, the early development of large open water areas in the Beaufort and Chukchi seas led to sea surface temperature anomalies in excess of 2.5°C [(**Figure 7**]), leading to more than 2 m of basal melt by the end of summer [(Perovich et al., 2007]). Third, the Arctic has warmed in all seasons [(Serreze et al., 2009; Stroeve et al., 2011a]), leading not only to earlier melt onset and later autumn freeze-up [(Markus et al., 2009]), but also a reduced likelihood of unusually cold conditions that could bring about temporary recovery through natural climate variability.

However, even during decadal or multi-decadal periods of accelerated ice loss, climate model simulations such as those from CCSM3 and CCSM4 simulations [(Holland et al., 2007, Kay et al., 2011]), show there can be several-year periods of slow ice loss or even temporary increases in extent. Thus, while the observed trend is steeper over the past decade compared to the earlier part of the record, it is uncertain if this pattern will be sustained. The higher extent for September 2009 relative to 2007 and 2008 may have suggested a temporary recovery, yet September 2010 and 2011 saw less ice compared to 2009 despite a winter circulation pattern that should have helped to favor ice retention through the summer melt season in 2010 [(Stroeve et al., 2011b]), and generally less favorable summer conditions for substantial ice loss in summer of 2011.

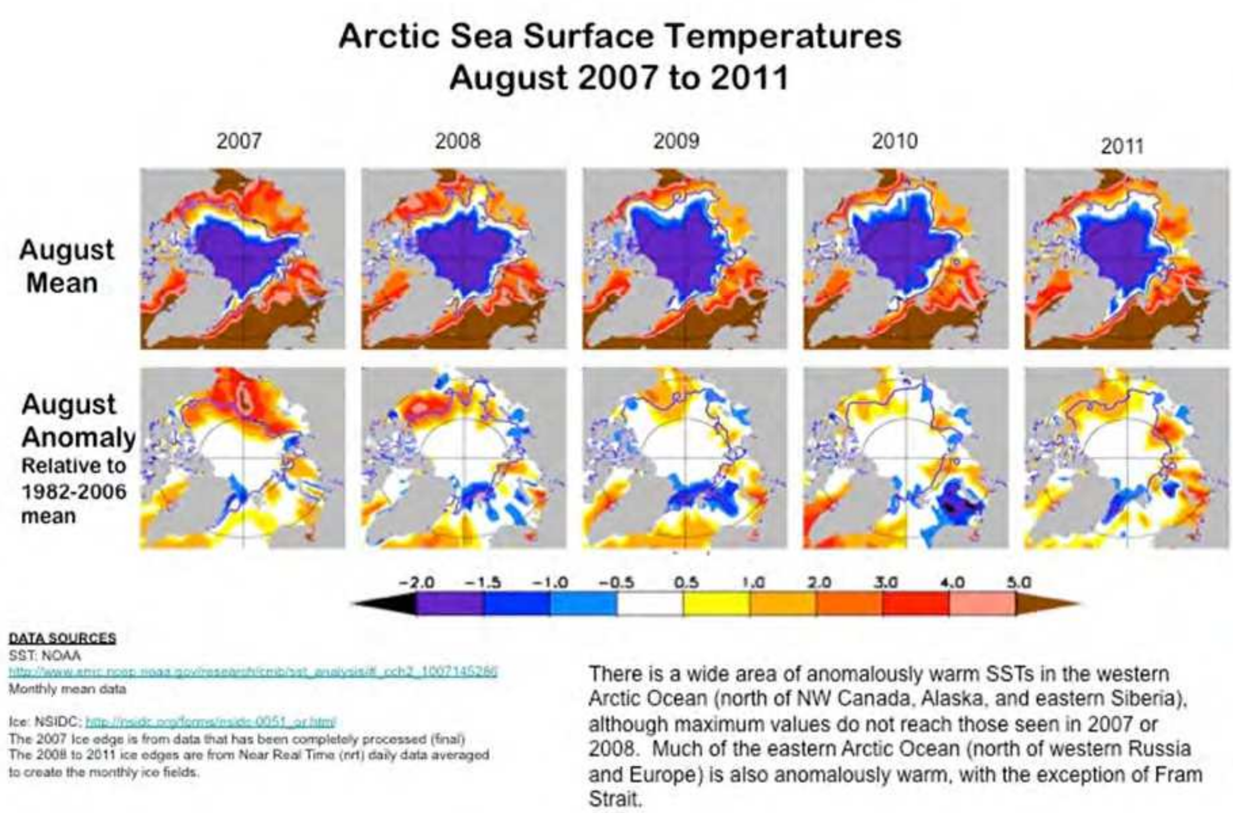


Fig. 7. Mean August sea surface temperatures and anomalies for 2007 through 2011. Anomalies are computed relative to the 1982-2006 mean. Credit: Michael Steele and Wendy Ermold, Polar Science Center, Applied Physics Laboratory, University of Washington.

4. Future ice conditions

Climate models have long suggested that as atmospheric greenhouse gas concentrations increase, the Arctic Ocean will likely become ice-free during. In some of the model projections, this seasonally ice-free Arctic state is expected to occur sometime after 2100 whereas in other models the estimate is as early as 2050 [(IPCC, 2007]). Figure 8 shows a comparison between the observed September ice extent from 1953 to 2010, based on a combination of early ship, aircraft, satellite and submarine records together with the modern satellite data record [(Stroeve et al., 2007; Stroeve et al., 2008]), and 15 models participating in the IPCC AR4 report using the "business as usual (A1B)" GHG scenario. It is clear that all models show declining September sea ice extent, with some models indicating that the Arctic will become ice-free sometime during the latter half of this century and others suggesting it will happen sometime after 2100. However, there is significant spread in the simulated September ice extents.

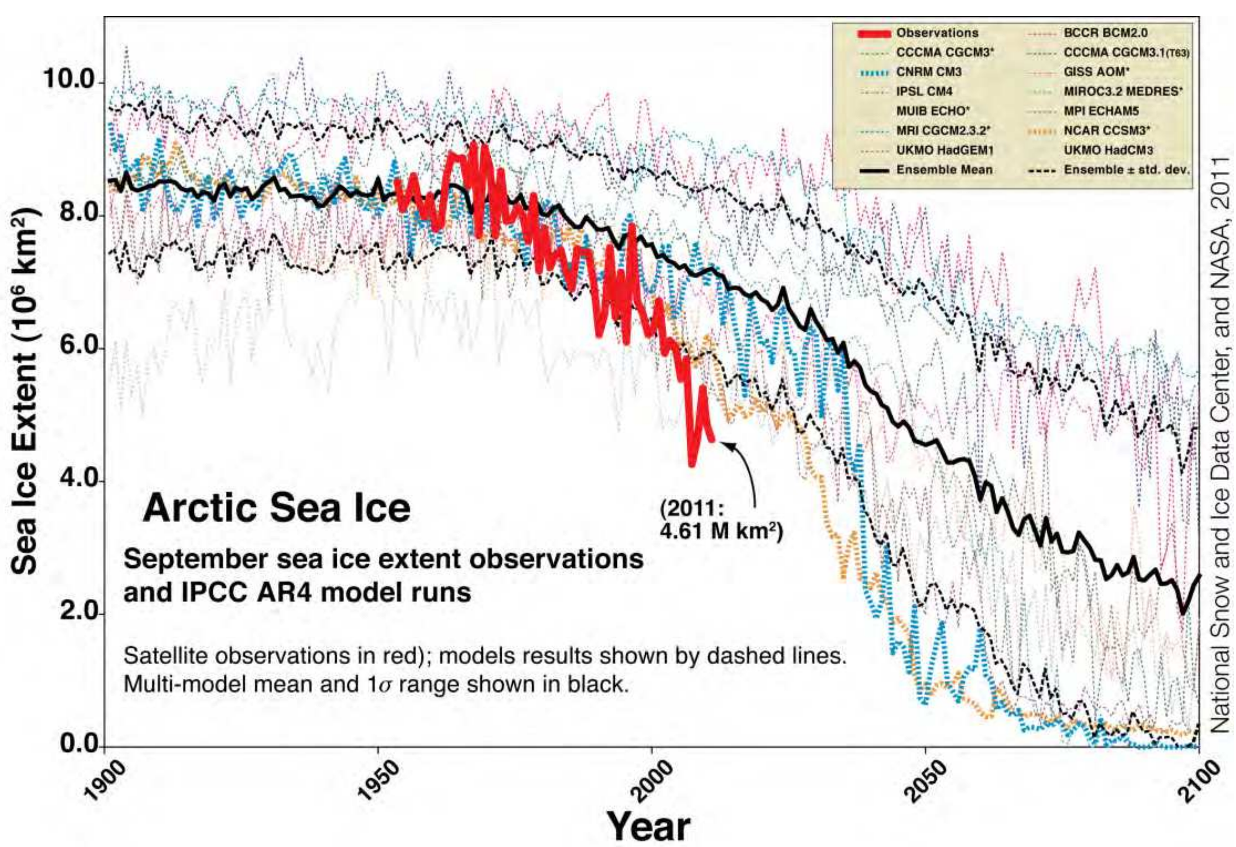


Fig. 8. Comparison between Global Climate Model (GCM) simulations of September sea ice extent (individual color lines) and observations (shown in red). The solid black line represents the ensemble mean and the dotted black lines are the +/- one standard deviation of the ensemble mean. Figure updated from Stroeve et al., 2007.

While the model simulated September ice extents are in qualitative agreement with the observations that the sea ice has been in declining during the observational record, it is clear that the models are failing to capture the rate of decline. From 1953 to 2010, the observed rate of decline in the September ice extent is -8.8 $\pm$ 0.6 percent per decade. The multi-model ensemble mean is only -2.8 $\pm$ 0.2 percent per decade. Over the modern satellite data record (e.g. 1979-2010) the model ensemble mean increases to -4.4 $\pm$ 0.2 percent per decade, but it remains three times less than the observed (-12.5 $\pm$ 1.6 percent per decade) trend. The inability of the climate models to accurately simulate the observed rate of decline has raised speculation that the Arctic may become seasonally ice-free sooner than the climate models predict.

As mentioned earlier, it appears that both anthropogenic forcing and natural climate variability are responsible for the observed decline. However it is clear from climate model simulations that as atmospheric GHGs continue to increase, the Arctic will transition towards a seasonally ice-free Arctic state. However, climate model simulations also suggest the natural climate model variability can exert a strong influence on the sea ice trends, especially on sub-20 year time-scales. Thus, while the Arctic ice cover appears to be on track to become ice-free in summers in the future, it is entirely possible to have periods of temporary recovery [Kay et al., 2011].

5. Climate Implications

5.1 Reduced sea ice amplifies warming

Except during summer, the sea ice cover insulates a relatively warm Arctic Ocean from a much colder atmosphere. As mentioned earlier, with less sea ice at summer's end and more open water, the ocean absorbs the suns energy that would normally be reflected by the ice cover and the ocean mixed layer heats up. As temperatures drop in autumn and the sun disappears for winter, the ocean will eventually lose the extra mixed layer heat that it gained in summer and the ice will form. This results in large heat transfers from the ocean back to the atmosphere in autumn, most pronounced at the surface but also extending upwards in the lower troposphere. This "amplified warming" is a prominent feature of climate models. **Figure 9** shows how the pattern of cold-season warming over the Arctic Ocean grows with time in the model simulations. Additionally, the warming is focused near the surface, but extends up to considerable height within the troposphere. Analysis of the GCMs participating in the IPCC 2007 report reveal consistency in the seasonality and vertical structure of this warming, but with different timings, magnitudes and spatial patterns of change [(Serreze et al., 2009]). This is in part a result of inter-model scatter in the timing of the sea ice cover retreat through the coming century as well as differences in patterns of atmospheric heat transport, vertical mixing, cloud processes and water vapor. Atmospheric circulation and precipitation patterns are one of the least robust signals in climate model simulations [(e.g. Deser et al., 2011]).

One implication of amplified Arctic temperatures is the potential to hasten permafrost degradation [(e.g. Lawrence et al., 2008]). Permafrost is frozen land that remains below 0^oC for at least two years. In the Northern Hemisphere, permafrost occupies approximately 22.79 million km^2 (about 24% of the exposed land surface) [(Zhang et al. 2003]). This permafrost contains a significant store of the Earth's deposits of organic carbon. Observations indicate that permafrost in the Arctic is warming [(e.g. Isaksen et al., 2007;

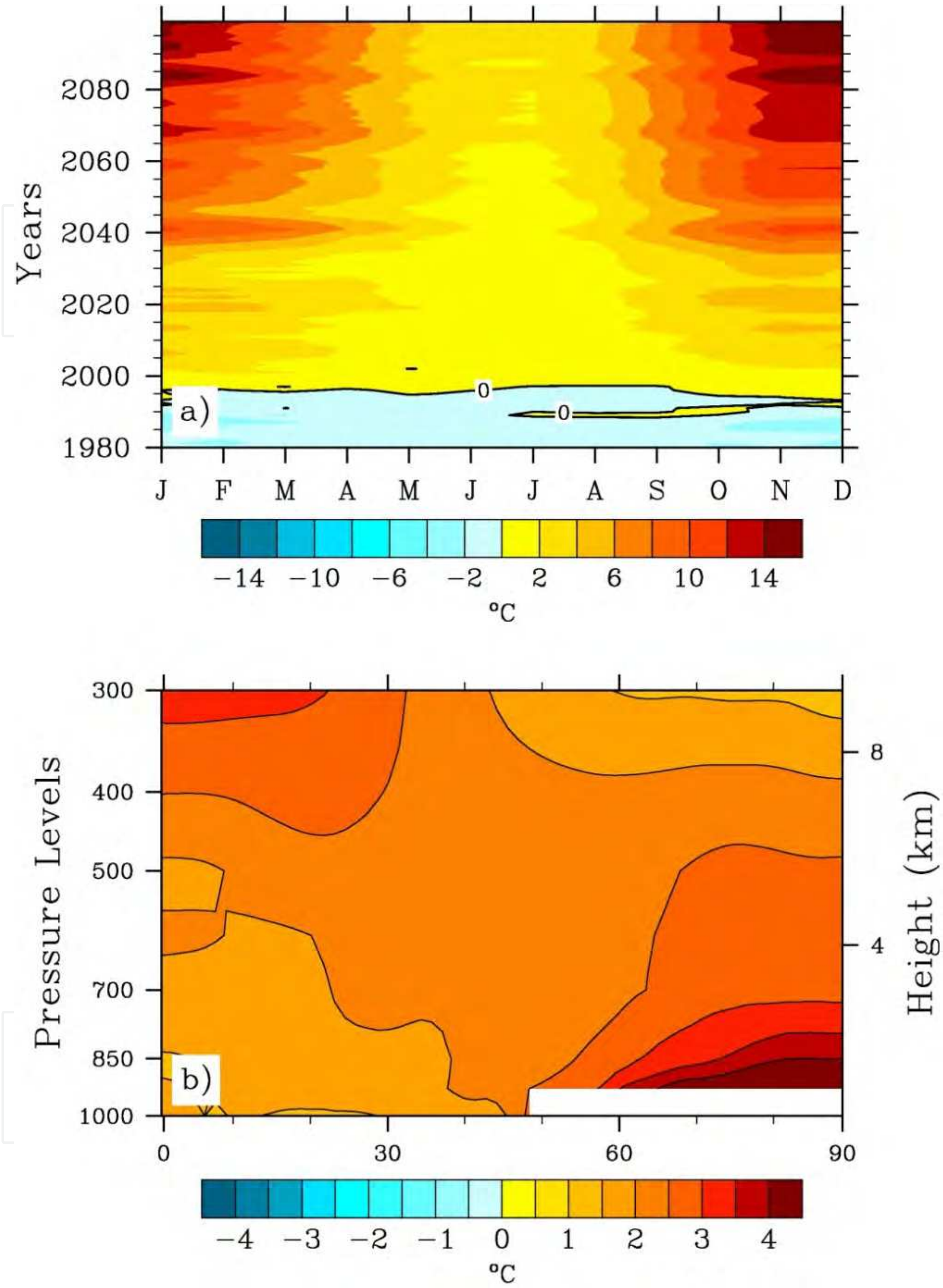


Fig. 9. Air temperature simulations from the NCAR CCSM3 global climate model using the IPCC A1B emission scenario. The top figure shows the near surface (2 meter) air temperature anomalies by month and year over the Arctic Ocean while the bottom figure shows the latitude by height plot of the October through March temperature anomalies for 2050-2059 relative to 1979-2007. Figure from Serreze et al., 2009.

Osterkamp, 2007; Jorgenson et al, 2001]), and this warming is already leading to increased emissions of carbon dioxide and methane [(e.g. Schuur et al., 2009]). Climate models suggest that as much as 90% of the near-surface permafrost may disappear by the end of this century [(Lawrence et al., 2008]). This has the potential to release large amounts of carbon into the atmosphere and contribute to further warming.

Another potential impact of Arctic amplification is the potential to melt more of the land ice in the Arctic, including the ice on the Greenland ice sheet. More melting of land ice in the Arctic has the potential to raise global sea level by several meters.

5.2 Altered weather patterns

Heating the atmosphere over the Arctic Ocean alters the temperature gradient from the equator to the poles. This impacts both the atmosphere's static stability and the atmospheric thickness gradient. A weaker thickness gradient toward the poles results in weaker vertical wind speed (or wind shear). This impacts on the development, tracks and strengths of storms and the precipitation they generate, that may well extend beyond the Arctic. For example, there is some evidence that autumn sea level pressure fields following summers with less sea ice exhibit higher pressures over much the Arctic Ocean and the North Atlantic, compensated by lower pressures in the mid-latitudes, otherwise known as the negative phase of the AO [(e.g. Francis et al., 2009]). This can have wide-spread impacts on temperatures and precipitation in the Northern Hemisphere [(e.g. Hurrell, 1995]).

There is broad agreement in climate models that warming will lead to increased precipitation in the northern high latitudes [(Kattsov et al., 2007; Finnis et al., 2007; Deser et al, 2010]). This is linked to the influence of more open water on atmospheric temperatures and the ability of a warmer atmosphere to hold more water vapor. However, different modeling studies have come to vastly different conclusions as to the spatial distribution of these precipitation changes. While many models suggest a decrease in cyclone frequency, but more intense storms, other studies suggest increased frequency of intense storms [(Lambert and Fyfe, 2006]), while other studies suggest precipitation increases are a result of poleward shifts in storm tracks (Yin, 2005).

Simmonds and Kaey (2009) suggest the loss of the summer Arctic sea ice cover has led to increased strength of September cyclones. This link is associated with increased sensible and latent heat fluxes associated with more open water. Stroeve et al. [(2011c]) further note there has been a corresponding increase in autumn precipitation associated with more frequent and stronger cyclones in years that had anomalously low September sea ice extent [(**Figure 10**]). However cause and effect remain unclear. While there has been anomalously more sensible and latent heat fluxes, as well as more precipitable water vapor over the regions where the ice cover has retreated, the increase in precipitation is primarily linked to a shift in atmospheric circulation towards more frequent and intense cyclones in the Atlantic sector of the Arctic. Thus, the absence of a clear link between the spatial patterns of recent precipitation changes and sea ice extent anomalies may suggest the link between recent changes in cyclone activity and sea ice loss is premature.

However, it is entirely possible that the recent declines in the sea ice cover have in part forced the observed circulation changes [(Francis et al., 2009; Overland and Wang, 2010]). As changes in the temperature structure in the Arctic atmosphere become more pronounced in the coming decades as the summer sea ice cover continues to decline, a clearer link between corresponding atmospheric circulation and precipitation changes should emerge.

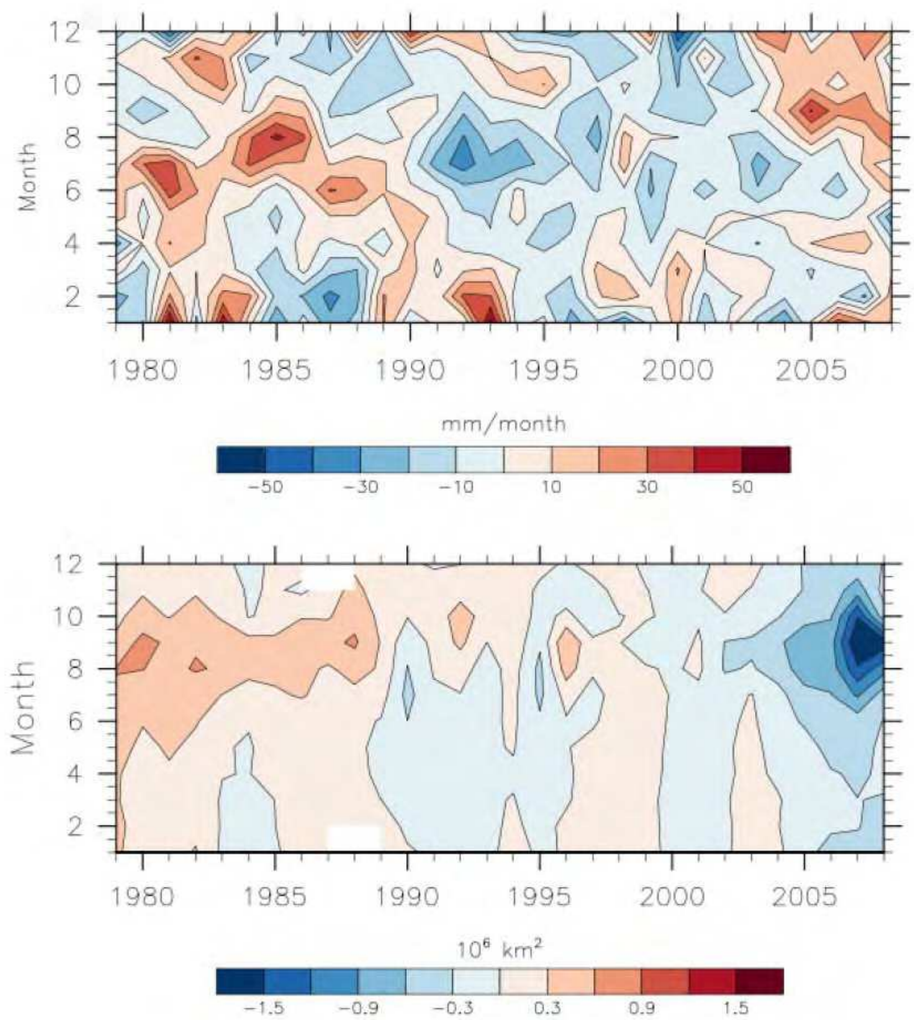


Fig. 10. Cyclone associated precipitation anomalies averaged for all regions north of 60ºN (top) and corresponding sea ice extent anomalies (bottom). Anomalies are computed with respect to the 1979 to 2009 mean. Figure from Stroeve et al., 2011c.

6. Summary

The Arctic sea ice is currently in a state of accelerated decline. This decline has been linked to a combination of natural climate variability and anthropogenic forcing linked to rising concentrations of atmospheric greenhouse gases. Global climate models suggest that as the amount of atmospheric CO_2 continues to increase, the Arctic will eventually transition towards ice-free conditions in summer, though there could be periods of temporary recovery on that trajectory. Given the fact that the currently observed rate of decline exceeds that simulated by our most advanced climate models, it is entirely possible that a seasonally ice-free Arctic state may be achieved within the next 20 to 30 years. The loss of the Arctic summer sea ice cover will have profound implications for our climate. Today we are already seeing the impacts of amplified warming over the Arctic linked to the loss of the summer ice cover, with the potential to further amplify warming by releasing carbon stored in the permafrost and further melting of the Arctic's ice caps and glaciers. This warming will additionally invoke changes in atmospheric circulation. While there is at the moment no universal consensus regarding the changes in weather patterns expected, a common thread in the climate model simulations is that the changes will be significant and affect areas well beyond the boundaries of the Arctic.

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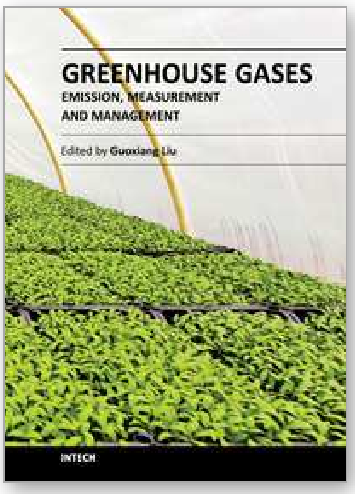

Greenhouse Gases - Emission, Measurement and Management
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Understanding greenhouse gas sources, emissions, measurements, and management is essential for capture, utilization, reduction, and storage of greenhouse gas, which plays a crucial role in issues such as global warming and climate change. Taking advantage of the authors' experience in greenhouse gases, this book discusses an overview of recently developed techniques, methods, and strategies: - A comprehensive source investigation of greenhouse gases that are emitted from hydrocarbon reservoirs, vehicle transportation, agricultural landscapes, farms, non-cattle confined buildings, and so on. - Recently developed detection and measurement techniques and methods such as photoacoustic spectroscopy, landfill-based carbon dioxide and methane measurement, and miniaturized mass spectrometer.

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