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Processes and impacts of Arctic amplification: A research synthesis

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ABSTRACT

The past decade has seen substantial advances in understanding Arctic amplification — that trends and variability in surface air temperature tend to be larger in the Arctic region than for the Northern Hemisphere or globe as a whole. We provide a synthesis of research on Arctic amplification, starting with a historical context and then addressing recent insights into processes and key impacts, based on analysis of the instrumental record, modeling studies, and paleoclimate reconstructions. Arctic amplification is now recognized as an inherent characteristic of the global climate system, with multiple intertwined causes operating on a spectrum of spatial and temporal scales. These include, but are not limited to, changes in sea ice extent that impact heat fluxes between the ocean and the atmosphere, atmospheric and oceanic heat transports, cloud cover and water vapor that alter the longwave radiation flux to the surface, soot on snow and heightened black carbon aerosol concentrations. Strong warming over the Arctic Ocean during the past decade in autumn and winter, clearly associated with reduced sea ice extent, is but the most recent manifestation of the phenomenon. Indeed, periods of Arctic amplification are evident from analysis of both warm and cool periods over at least the past three million years. Arctic amplification being observed today is expected to become stronger in coming decades, invoking changes in atmospheric circulation, vegetation and the carbon cycle, with impacts both within and beyond the Arctic.

1. Introduction

In 1896, the Swedish scientist Svante Arrhenius argued that changes in the concentration of carbon dioxide in the atmosphere could alter the earth's surface temperature and that the temperature change would be especially large in polar latitudes (Arrhenius, 1896). This appears to be the first formal recognition of what has come to be called Arctic amplification — temperature variability and trends in the Arctic region tend to be larger than trends and variability for the northern hemisphere or the globe as a whole. Studies of the instrumental record, reconstructions of past climates from proxy records and experiments with global climate models confirm that Arctic amplification is a characteristic feature of the climate system. While the instrumental network for the Arctic is temporally inhomogeneous and insufficiently dense to capture some of the details of temperature variability and change, particularly over the ocean, it is abundantly clear that there have been periods of strong Arctic warming or cooling throughout the 20th century. Arctic amplification is prominent in annual surface air temperature trends for the past 50 years (Fig. 1) and especially to anomaly fields for the past decade, 2000–2009. Recent Arctic amplification is best expressed during the autumn and winter seasons, and is much weaker for spring and summer (Fig. 2). With the exception of the Antarctic Peninsula and the West Antarctic ice sheet (Vaughan et al., 2003; Steig et al., 2009), warming over southern high latitudes has been modest in comparison to the Arctic.

Arctic amplification is a near universal feature of climate model simulations of the planet's response to increasing atmospheric greenhouse gas concentrations (e.g., Manabe and Stouffer, 1980; Hansen et al., 1984; Robock, 1983; Washington and Meehl, 1996; Holland and Bitz, 2003; Hall, 2004; Winton, 2006). Based on a set of coupled models participating in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), Winton (2006) find a mean annual Arctic (60°N–90°N) warming that is, on average, 1.9 times greater than the global mean warming at the time of carbon dioxide doubling. Evidence is strong that as Arctic amplification continues to grow, it will have impacts extending beyond the Arctic (Lawrence et al., 2008). Within the Arctic, it already appears to be contributing to greening of coastal tundra (Bhatt et al., 2010) and altered wind patterns (Overland and Wang, 2010).

Why does Arctic amplification occur? Discussion often focuses on albedo feedback, the process identified by Arrhenius. Viewed in its simplest sense, initial warming will melt some of the Arctic's highly reflective (high albedo) snow and ice cover, exposing darker underlying surfaces that readily absorb solar energy, leading to further warming and further retreat of snow and ice cover. This feedback can work in reverse whereby initial cooling leads to expansion of the Arctic's snow and ice cover, leading to further

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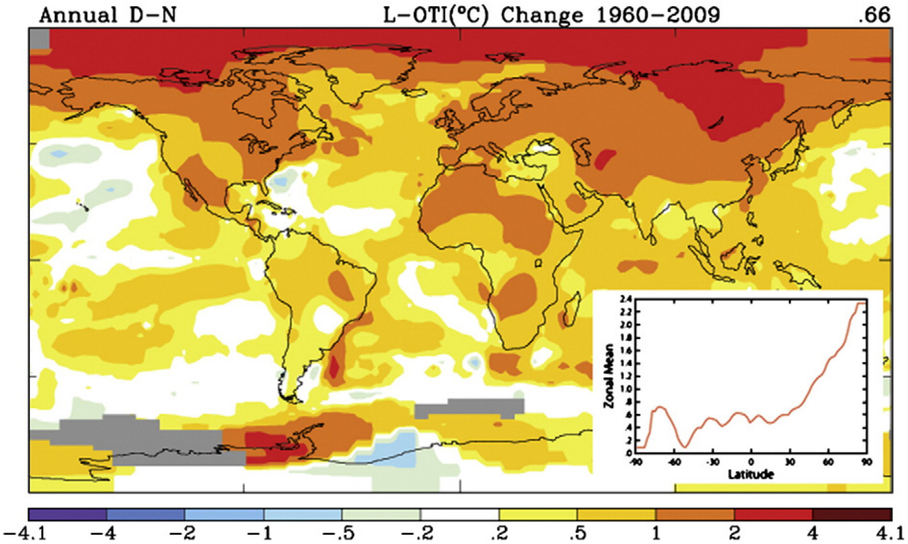

Fig. 1. Linear trends in annual mean surface air temperature for the period 1960–2009, based on the National Aeronautics and Space Administration Goddard Institute for Space Sciences (NASA GISS) temperature analysis (http://data.giss.nasa.gov/gistemp). The inset shows linear trends over the 50-year analysis period averaged by latitude.

cooling. However, as developed below, Arctic amplification as is presently understood has a suite of causes, operating on different temporal and spatial scales. Prominent among these are expansion or retreat of the Arctic sea ice cover altering vertical heat fluxes between the Arctic Ocean and the overlying atmosphere (Serreze et al., 2009; Screen and Simmonds, 2010a,b), changes in atmospheric and oceanic heat flux convergence (Hurrell, 1996; Graversen et al., 2008; Chylek et al., 2009; Yang et al., 2010), and changes in cloud cover and water vapor content that affect the downward longwave radiation flux (Francis and Hunter, 2006) arising from processes either within the

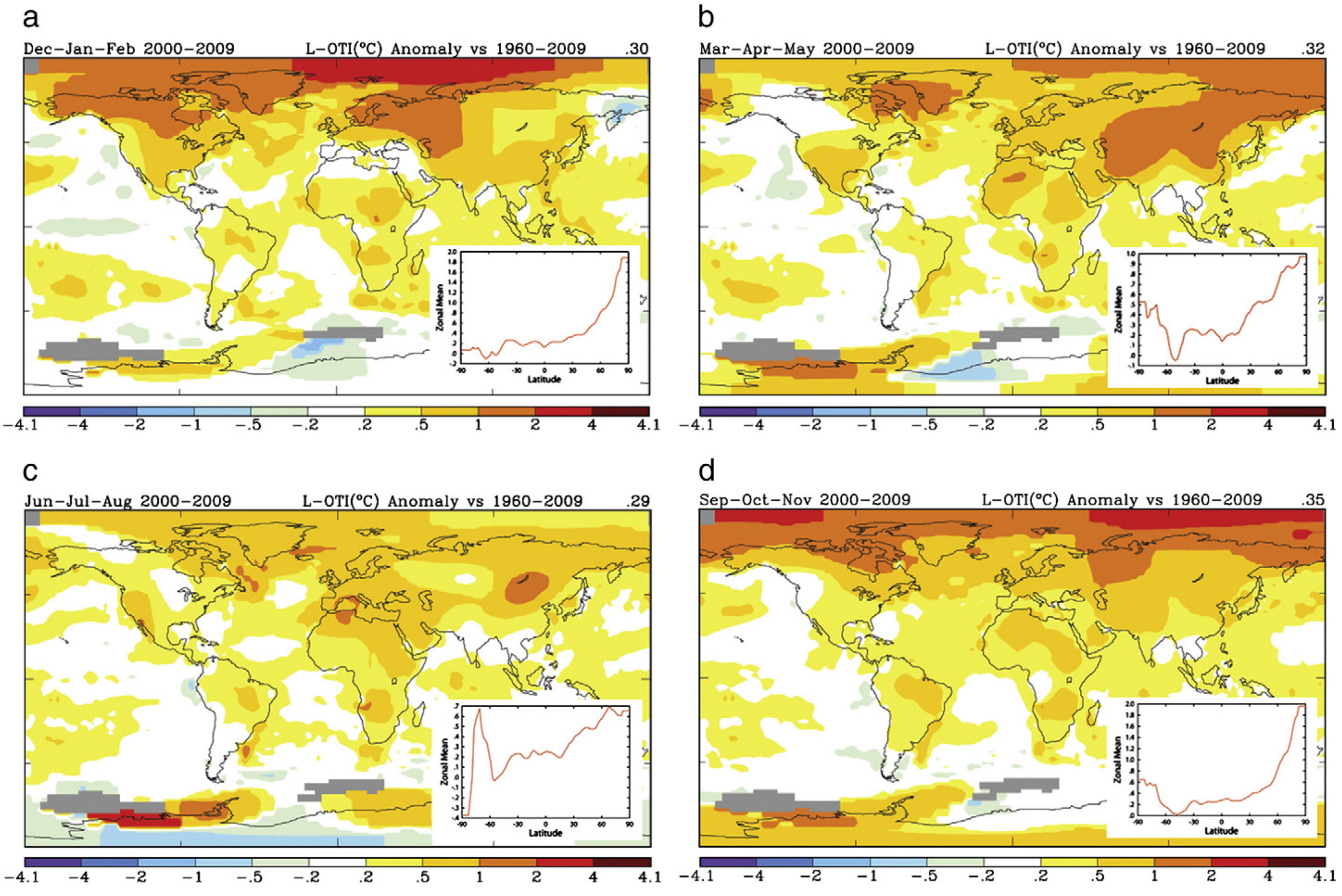

Fig. 2. Anomalies in winter (a, December–February), spring (b, March–May), summer (c, June–August) and autumn (d, October–November) temperature for the decade 2000–2009 computed with respect to the reference period 1960–2009. The insets show anomalies averaged by latitude. Results are based on the NASA GISS temperature analysis, http://data.giss.nasa.gov/gistemp.

Arctic or in response to alterations in atmospheric energy flux convergence (Abbot et al., 2009; Graversen and Wang, 2009). Other studies point to impacts of soot on snow (Hansen and Nazarenko, 2004) and of heat absorbing black carbon aerosols in the atmosphere (Shindell and Faluvegi, 2009). Different processes can work together. For example, a change in atmospheric heat flux convergence that leads to warming may result in reduced sea ice extent that furthers the warming.

2. Observed characteristics

2.1. Early studies

Recognition of Arctic amplification grew through the 20th century, slowly at first, and then more quickly through the 1990s and into the present millennium as the observational database, models, and analysis techniques improved, and the effects of heightened concentrations of atmospheric greenhouse gasses emerged from the background of natural climate variability.

In his book "Climate through the Ages", the meteorologist C.E.P. Brooks (Brooks, 1949, p. 376) noted that winter temperatures had risen since 1850 in all the north temperate and Arctic regions. Winter temperatures in Spitzbergen, lying at roughly 80°N in the northernmost North Atlantic, rose by 9 °C between 1911–1920 and 1931–1935 compared to only 3 °C between 1851–1900 and 1901–1930 in Western and Central Europe. While the especially strong warming around Spitzbergen was attended by a regional poleward retreat of the sea ice edge, Brooks does not appear to have drawn conclusions from these observations.

As part of the Centenary Conference of the Royal Meteorological Society in 1950, Willett (1950) analyzed global temperature trends from the mid-nineteenth century onwards and found that annual and particularly winter temperatures had increased since 1885, especially in northern high latitudes, and referred to this as "the well-known warming which occurred in north polar latitudes". No counterpart was seen in the Southern Hemisphere. Willett invoked changes in atmospheric circulation as an explanation, namely longitudinal displacements of the Siberian polar anticyclone. Lysgaard (1950) came to similar conclusions and further showed that the sea level pressure gradient in the North Atlantic strengthened during the warming interval.

Callendar (1961) noted that the warming trend during preceding decades was significant from the Arctic down to about 45°N, but quite small in most regions below 35°N. He emphasized "the most spectacular climatic event" as the pronounced rise in temperature over most of the Subarctic during the 1920s and 1930s The temperature difference for 1921–1950 minus 1891–1920 for the latitude zone 60–73°N was 0.81 °C compared with 0.39 °C for the band spanning 25–60°N. Callendar discussed possible causes of the warming, including the potential role of back radiation from increasing carbon dioxide concentrations. Mitchell (1961) updated the Willett (1950) analysis and determined temperature changes weighted by the area of each latitude band instead of giving all stations equal weight. This reduced the magnitude of warming. The addition of data through 1959 also diminished the long-term warming signal for 1880–1959. However, the warming up to 1940 was still shown to be greater in high northern latitudes.

Stepping forward a couple of decades, Kelly et al. (1982) showed that during the 100 years from 1881 to 1980, trends in Arctic (65–85°N) annual temperatures were strongly correlated with hemispheric ones ($r = 0.81$), but were greater in magnitude and the changes were more rapid in the Arctic, particularly for the winter season. The range of variation of Arctic temperatures between the 1890s and 1940 was about three times that of the hemispheric variation.

2.2. A warming Arctic

By the mid 1990s, it was clear that, following a general cooling through about 1970, much of northern Eurasia and northwest North America were showing renewed warming stronger than that for the global average, primarily during winter and spring, partly compensated by cooling over northeastern North America. The mass balance of Arctic glaciers had become persistently negative, paralleling a global tendency. Evidence emerged of increased plant growth in the Arctic, and northward advance of the treeline. Alaskan permafrost was found to be warming and locally thawing. There were hints that air temperatures were also increasing over the Arctic Ocean. The growing satellite record indicated a decline in Arctic sea ice extent, most pronounced in September, the end of the melt season. It was furthermore established that increasingly warm waters were entering the Arctic Ocean from the Atlantic. As stated in a review paper published in the year 2000, "Taken together, these results paint a reasonably coherent picture of change, but their interpretation as signals of enhanced greenhouse warming is open to debate" (Serreze et al., 2000).

At issue was the cause of the renewed Arctic warming and comparisons with expectations from global climate model simulations of responses to atmospheric greenhouse loading. Experiments from first generation models (e.g., Manabe and Stouffer, 1980; Hansen et al., 1984) and more advanced ones participating in the second assessment report of the IPCC, broadly indicated a preference for the strongest warming to emerge over the Arctic Ocean, most pronounced for autumn and winter. Observations, by contrast, showed the strongest warming over land, and for winter and spring. The longest available air temperature records for the Arctic Ocean, from the Russian "North Pole" drifting ice camps, indicated statistically significant upward trends in temperature only for May and June and for summer as a whole (Martin et al., 1997). To complicate comparisons, the magnitude and spatial structure of warming was found to vary greatly across different climate models. Serreze et al. (2000) also recognized that comparisons between observed trends and projected conditions well into the future may not be especially meaningful.

As first pointed out by James Hurrell (1995, 1996), the strong warming over Eurasia and northwest North America, as well as the cooling over northeastern North America, had what appeared to be a rather straightforward explanation — a positive tendency over the preceding 20 years in the winter phase of the North Atlantic Oscillation (NAO), a large-scale pattern of atmospheric variability linking the strengths of the semi-permanent cells of sea level pressure known as the Icelandic Low and the Azores High. Simply put, changing wind patterns altered patterns of temperature advection, leading to temperature trends with strong regional expressions. Greenhouse warming need not be invoked — natural multi-decadal (low frequency) climate variability provided a sufficient explanation. A slew of papers followed, many (e.g., Moritz et al., 2002) looking at climate links in the larger-scale framework of the Northern Annular Mode (NAM) popularized by Thompson and Wallace (1998); the NAO can be viewed as the North Atlantic component of the NAM.

In 2002, Igor Polyakov and colleagues published an analysis of annual surface air temperature anomalies averaged for the region north of 62°N, extending back 125 years (Polyakov et al., 2002). Their record blended measurements from land stations (primarily coastal), the Russian North Pole drifting ice camps, and buoys over the Arctic Ocean. For the final 17 years of the record (1985–2001), the computed trend of approximately 0.6 °C per decade was found to be twice the corresponding value for the Northern Hemisphere as a whole. By sharp contrast, a trend calculated from 1920 to present yielded a small Arctic cooling. For the period 1901 to 1997, there was no significant difference between the trend for the Northern Hemisphere as a whole and for the Arctic. Given the lack of enhanced high latitude warming when the trend is computed over the longest possible record, Polyakov and colleagues concluded that there is no Arctic amplification and that the more notable feature of the Arctic is its pronounced low-frequency variability.

This raised a number of questions. Is it valid to dismiss Arctic amplification by focusing only on the long-term trend? Were the results influenced by a bias towards records from land areas, when climate models were suggesting that amplification, when it emerges, will tend to be strongest over the Arctic Ocean? Such questions led Johannessen et al. (2004) to enhance the data set used by Polyakov et al. (2002) by including additional land stations as well as output from the European Centre for Medium-Range Weather Forecasts numerical weather prediction model (starting in 1995) to provide better coverage over the Arctic Ocean. While their analysis captured the major features noted in other studies, namely substantial high latitude warming from about 1920–1940, followed by cooling to about 1970, then renewed warming extending to the end of the record, the recent warming was seen to increase poleward of the Arctic Coast. This was some of the first evidence of the warming over the Arctic Ocean projected by many climate models.

Meanwhile, as pointed out in a number of studies, from peak positive values in the late 1980s to mid 1990s, the winter index of the NAO had regressed and began alternating between positive and negative states. Spatial patterns of surface air temperature anomalies changed, but the basic path nevertheless continued to be one of warming (Serreze and Francis, 2006).

Based on data from land stations north of 64°N through the year 2008, Chylek et al. (2009) showed that the earlier 20th century period of Arctic amplification, in their study identified as covering the period 1910–1940, proceeded at a faster rate than the more modern warming identified for the period 1970–2008. The degree of Arctic amplification, assessed as the ratio in the annual mean trend for the region 70–90°N to the trend for the globe as a whole, was 2.9 for the 1970–2008 period, compared with 6.9 for 1910–1940. For winter the ratios for the two periods, respectively, were 2.9 and 12.5, compared to 3.6 and 5.7, respectively, for summer. Corresponding ratios during the cooling period from 1940 to 1970 reached 16.7 for autumn and 16.0 for spring (stronger cooling in the Arctic), with an annual value of 12.5. More recently, Bekryaev et al. (2010) document a northern high-latitude (for land stations north of 59°N) warming rate of 1.36 °C per century for the period 1875–2008, almost twice as strong as the Northern Hemisphere trend (0.79 °C per century), with an even stronger warming rate for the last decade (1.35 °C/decade). Their study included many sites along the Arctic Ocean coast. Fig. 3 shows the annual and seasonal temperature time series from that study.

Surprisingly, apart from the effort by Johannessen et al. (2004), none of the studies discussed above specifically examined the Arctic Ocean, where the strongest Arctic amplification is projected to occur. While coastal sites certainly provide some information as to conditions over the ocean (the Arctic Ocean warming seen in Fig. 2 is strongly influenced by interpolation from coastal stations), a fuller picture requires the use of gridded fields from satellite retrievals or atmospheric reanalyses. Atmospheric reanalyses provide long time series of atmospheric and surface conditions through data assimilation techniques that blend observations with short-term forecasts from a numerical weather prediction model. Time series from atmospheric reanalyses are standard climate research tools.

Serreze et al. (2009) examined the evolution of temperatures over the Arctic Ocean from 1979 to 2007 using data from two different atmospheric reanalyses. Anomalies were computed with respect to the period 1979–2007. Starting in the late 1990s, surface air temperature anomalies over the Arctic Ocean were seen to turn positive in autumn, growing in subsequent years, and building into winter. Development of the autumn warming pattern was found to align with the observed reduction in September sea ice extent, with the temperature anomalies strengthening from the lower troposphere to the surface. The recent autumn warming was found to be stronger over the Arctic Ocean than over Arctic land areas and lower latitudes. No enhanced surface warming signal was found in summer.

Screen and Simmonds (2010a) examined temperature trends from 1989 to 2008 using output from ERA-Interim, the newest reanalysis from the European Centre for Medium Range Weather Forecasts. They confirmed that the strongest recent warming lies over the Arctic Ocean, most pronounced in autumn and winter, and strongly allied with the observed downward trend in September sea ice extent.

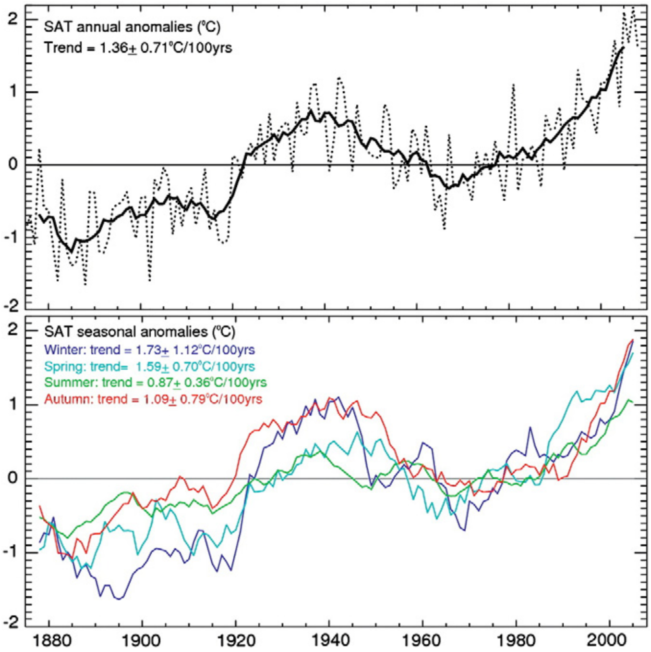

Fig. 3. Composite time series of the (top) annual and (bottom) seasonal surface air temperature anomalies (°C) for the region poleward of 59°N. The dotted lines show unsmoothed values, the solid lines are seven year running means. The liner trends listed in the legend are computed using data for the period 1900–2008 (from Bekryaev et al., 2010). Note the strong warming, from about 1920–1940, strong cooling until about 1970, and renewed warming through the end of the record.

3. Physical processes

Preceding discussion has already introduced some of the physical processes that underlie Arctic amplification. Here, we examine these processes in more detail, and how they relate back to both Arctic amplification now being observed and projections from climate models.

3.1. Sea ice loss

Except for summer, the Arctic sea ice cover insulates a relatively warm Arctic Ocean from a much colder atmosphere. Removing or weakening the insulating sea ice cover will result in warming of the overlying atmosphere.

Consider a climate forcing that acts to warm the Arctic. In response to this forcing, the summer sea ice melt season will lengthen and intensify. As the ice melts, dark open water areas are exposed that readily absorb solar radiation, increasing the sensible heat content in the top 20 m or so of the ocean (known as the mixed layer). This will foster further melt. In other words, summer sees a stronger net transfer of heat (net surface flux) than there used to be from the atmospheric column into the ice/ocean column. Summer ends and the sun sets over the Arctic Ocean. As illustrated in Fig. 4, with more open water and more heat in the ocean mixed layer, there will then be larger heat transfers (longwave radiation, latent and sensible heat fluxes) from the ocean back to the atmosphere. The warmer atmosphere will also radiate more strongly back to the surface. With little or no solar radiation, the ocean will eventually lose the extra mixed layer heat that it gained in summer, and sea ice will form. While this will reduce heat fluxes to the atmosphere, there will still be a significant upward heat flux due to latent heat release associated with sea ice growth. 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

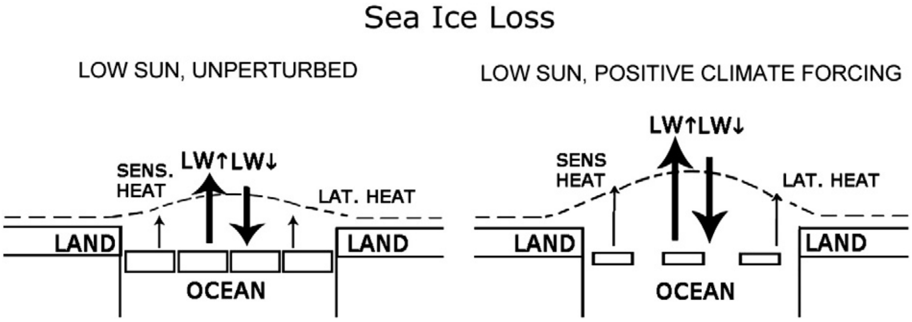

Fig. 4. Schematics of the surface energy budget of the Arctic Ocean, contrasting the situation during the low-sun period for (left) an unperturbed Arctic and (right) in response to a positive (warming) climate forcing that results in decreased ice concentration and thickness. The dotted line is an arbitrary isotherm in the lower troposphere; warming over the Arctic Ocean bows the isotherm upward. SW = shortwave radiation flux, LW = longwave radiation flux, Sens. Heat = sensible heat flux, Lat. Heat = latent heat flux.

ice will more readily melt out the next summer, meaning more open water at summer's end with more heat in the mixed layer, and so on.

This mechanism of Arctic amplification will hence have a pronounced seasonal expression, strongest in the low sun period, especially autumn, and weaker in summer, when the melting ice cover and heating of the ocean mixed layer (the downward net surface heat flux) will limit the rise in surface air temperature. The process can of course also work in reverse, where an initial cooling leads to more extensive and thicker ice, further reducing the air temperature.

As assessed over the modern satellite record, 1979 through the present, there are negative linear trends in Arctic sea ice extent for every month, with the strongest downward trend (11.5% per decade through 2010) at the end of the melt season in September. A record low was set in September 2007 (Stroeve et al., 2008; http://nsidc.com/arcticseaicenews/). The ice cover is also thinning (Nghiem et al., 2006; Maslanik et al., 2007; Kwok and Rothrock, 2009). The strong autumn and winter warming over the Arctic Ocean noted by Serreze et al. (2009) and Screen and Simmonds (2010a) is consistent with the effects of this ice loss. In a subsequent paper, Screen and Simmonds (2010b) quantify the magnitude of the ocean heat loss in autumn that drives the Arctic amplification.

3.2. Albedo feedback

Fig. 5 illustrates the direct effects of albedo feedback for land and ocean. Over land, the situation is fairly straightforward — warming leads to an earlier spring melt of the snow (early summer in high Arctic lands), meaning earlier exposure of the dark snow free surface, and stronger absorption of solar radiation. The warmer surface emits

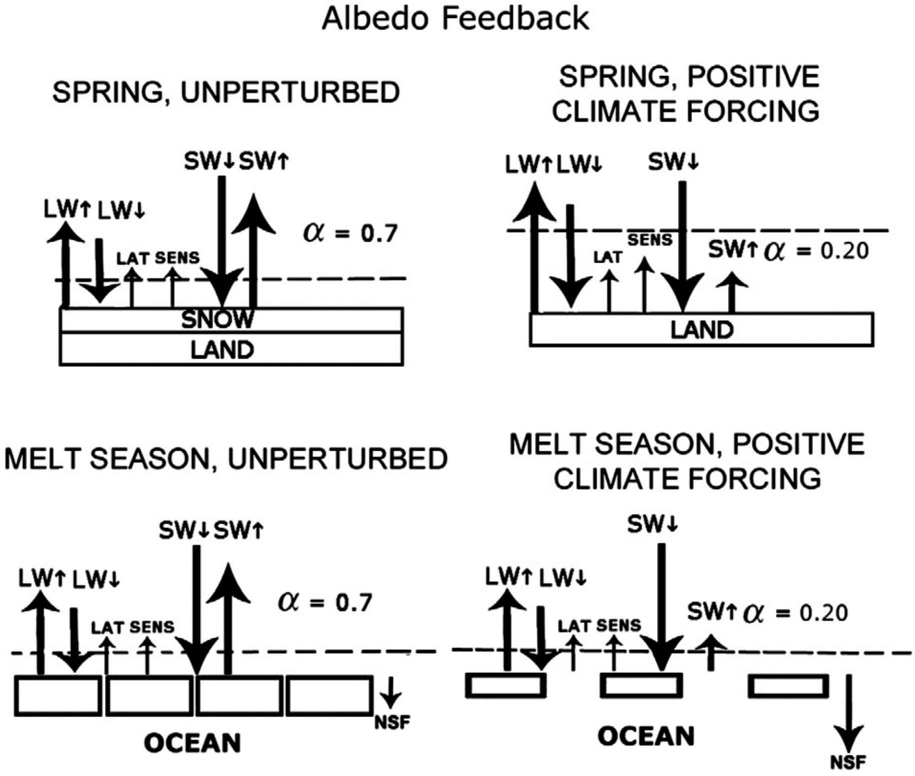

Fig. 5. Schematics of the effects of albedo feedback on the surface energy budgets over land and ocean, contrasting the situation for (left) an unperturbed Arctic and (right) in response to a positive (warming) climate forcing. The dotted line is an arbitrary isotherm in the lower troposphere; in a warmer atmosphere the isotherm is found at higher level in the atmosphere. Compared to land areas, albedo feedback has a small direct effect on surface air temperature over the ocean; the feedback is instead largely associated with a stronger net surface flux (NSF) into the Arctic Ocean column. With the onset of autumn, the heat gained by the ocean in summer is released back to the atmosphere. Net surface heat fluxes over land areas tend to be much smaller than over the ocean. SW = shortwave radiation flux, LW = longwave radiation flux, Sens. Heat = sensible heat flux, Lat. Heat = latent heat flux, NSF = net surface heat flux.

more longwave radiation, and turbulent heat fluxes are stronger. The air temperature is hence higher with a stronger longwave radiation flux back to the surface. Brown et al. (2010) examined trends in Arctic (north of 60°N) snow cover extent (coverage in square km) during the spring melt period (May–June) from ten different data sources. From their multi-dataset approach, they compute a 46% reduction in Arctic snow covered area in June and a 14% reduction in May over the period of record 1967–2008. This may drive some of the spring and summer warming over land seen in Fig. 2.

The situation over the Arctic Ocean is as described in Section 3.1. In a warmer climate, the summer sea ice melt season lengthens and intensifies, exposing more dark open water areas that readily absorb solar radiation, fostering further melt of the high albedo ice and increasing the sensible heat content of the mixed layer. Perovich et al. (2007) find that the reduction sea ice extent and concentration over the period 1979–2005 has led to increases in annual total solar radiation absorbed in the ocean mixed layer of as much as four percent per year in the Chukchi Sea and adjacent regions. Because the effect of the lower albedo is to foster more ice melt and add sensible heat to the ocean mixed layer, albedo feedback back over the ocean has smaller (compared to land) expressions in the longwave and turbulent fluxes and air temperature. The effects of the summertime ocean heat gain are primarily felt in autumn and winter as the ocean loses the extra heat gained in summer heat back to the atmosphere. Phrased differently, the Arctic amplification signal linked to sea ice loss (Fig. 4) can be viewed as a delayed seasonal expression of albedo feedback (albedo feedback can only work in a direct sense during sunlit periods). While the above discussion focuses on albedo feedback amplifying an initial warming, soot on snow linked to fossil burning may also be an important process reducing snow and ice albedo (Hansen and Nazarenko, 2004).

3.3. Horizontal heat flux convergence

Viewed as a whole, the Arctic region is characterized by both an atmosphere and oceanic heat flux convergence; in the annual mean, this convergence is primarily balanced by longwave radiation loss to space. A change in heat flux convergence will contribute to a change in Arctic temperature. Changing heat flux convergence may in turn alter atmospheric water vapor content and cloud cover that affect the surface temperature through their greenhouse effect, and (for cloud cover) altering solar input to the surface. Changing heat flux convergence may of course also alter sea ice extent and surface albedo.

Based primarily on output from the European Centre for Medium-Range Weather Forecasts ERA-40 reanalysis, Graversen et al. (2008) examined temperature trends as a function of latitude and height over the period 1979–2001. They found evidence of Arctic amplification throughout most of the troposphere. However, the pattern expected to be driven by snow and ice feedbacks, with a peak warming at the surface, was observed only in spring. In summer, the warming pattern was at a maximum between 800 and 600 hPa. From this, they argued that changes in the Arctic temperature field are largely due to changes in atmospheric heat transport into the Arctic, and not surface forcing. While this study met with some criticism, based on both problems with the reanalysis data that can affect trends and that the years with the lowest September sea ice extent are all after 2001, evidence for contributions by atmospheric circulation is strong. For example, Yang et al. (2010) examined the vertically-integrated poleward energy transport from 1979 to 2008 using reanalysis data in tandem with tropospheric temperatures derived from satellite data. They found that about 50% of the decadal warming trend in the Arctic (and 71% for the winter season) centered in the late 1990s was due to increasing poleward energy transport. Of the interval of cooling Arctic tropospheric temperatures centered on the late 1980s that they identify, about 25% was ascribed to a decrease in energy transport.

Turning to impacts of ocean circulation, Chylek et al. (2009) find that that Arctic air temperature changes are linked with the phase of the Atlantic Multi-decadal Oscillation (AMO). The AMO describes a multidecadal oscillation in North Atlantic sea-surface temperatures, with the largest changes in the higher latitudes of the Atlantic. The AMO can be linked to the strength of the thermohaline circulation that transports warm surface waters poleward (Ting et al., 2009). The pattern of Arctic warming from about 1920–1940, cooling up to about 1970, and the renewed warming follow the changing phase of the AMO. We are presently in a warm (positive) phase of the AMO. The 1920–1940 warming was centered in the Barents Sea. Bengtsson et al. (2004) argue that the cause of this warming was advection of relatively warm air from the southern Barents Sea to the Kara Sea and an associated increase in wind-driven oceanic inflow. This reduced sea ice extent in the area. Wood and Overland (2010) come to broadly similar conclusions. This is a good example of how atmospheric and oceanic processes can work together to result in Arctic amplification.

Bekryaev et al. (2010) suggest that there are two different spatial scales of Arctic amplification — large-scale and local. There is a seasonal cycle of Arctic amplification consistent with a large-scale winter and spring radiative mechanism and a year-round atmospheric transport mechanism, strongest in the cold season. The springtime polar amplification may result from snow albedo feedback. However, local scale polar amplification related to ice-albedo feedback mechanisms (especially reduced sea ice extent) is evident in autumn in maritime and coastal areas up to several hundred kilometers inland. These mechanisms are apparent during extended warm periods only (the 1930–1940s and recent decades).

3.4. Cloud cover and water vapor

While clouds reduce the shortwave flux to the surface through their high albedo, cloud cover (especially low-level Arctic stratus) augments the downward longwave flux to the surface; key factors influencing the longwave emission are cloud base temperature and whether the cloud cover is liquid phase, mixed phase or ice phase. Based on direct observations, such as from the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment (Intrieri et al., 2002) clouds warm the surface except for a brief period in summer, i.e., the surface net all-wave radiation flux is larger in the presence of cloud cover as compared to clear sky conditions. The net surface warming in the Arctic for most of the year is due to the absence of solar radiation during polar night and the high albedo of the sea ice surface. The shortwave cloud forcing and thus the net forcing are strongly sensitive to variations in the surface albedo (Curry and Ebert, 1992). The warming effect of clouds at the surface of the Arctic averaged over the year contrasts with lower latitudes, where clouds have a net cooling effect. This seasonality of cloud radiative forcing is captured in the models assessed in the IPCC AR4 (Vavrus et al., 2009).

Inspired in part from model experiments with an idealized “aquaplanet” with no albedo feedback (Alexeev et al., 2005; Langen and Alexeev, 2007), Graversen and Wang (2009) assessed surface air temperature changes in a coupled global climate model experiment with a fixed albedo and doubled atmospheric carbon dioxide. An increase in atmospheric water vapor and total cloud cover led to greenhouse effects larger in the Arctic than at lower latitudes, linked in part to the stably stratified conditions that often prevail in the Arctic which inhibit mixing. The importance of weak vertical mixing in Arctic amplification was recognized even in the early climate model experiment of Manabe and Wetherald (1975). While additional experiments by Graversen and Wang (2009) show that albedo feedback is a contributor to Arctic amplification, the amplification signal with variable albedo is only about 15% greater than with a fixed albedo (Fig. 6). On the basis of twelve climate models used in the IPCC Fourth Assessment report, Winton (2006) come to similar conclusions — while albedo feedback is important, the more

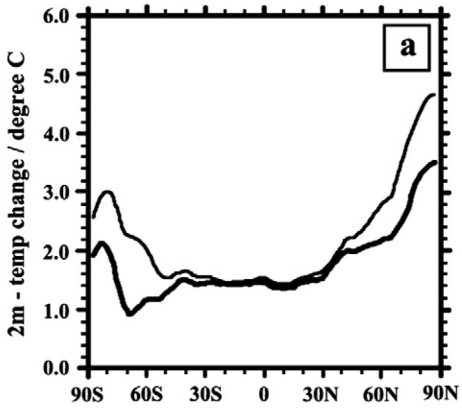

Fig. 6. Zonal mean 2-meter air temperature change with doubled carbon dioxide for experiments with locked albedo (thick line) and variable albedo (thin line) (from Graversen and Wang, 2009).

important processes are feedbacks linked to increased cloud cover and water vapor that influence the downwelling longwave radiation.

A question raised by Graversen and Wang (2009) is the extent to which the Arctic water vapor and cloud cover feedbacks are induced by local changes in the Arctic, or by larger scale changes in atmosphere energy transport such as discussed in the previous section. Regarding the latter, Solomon (2006) argues that in a warmer climate, the increased availability of atmospheric moisture will cause enhanced warming of the polar regions through promoting stronger cyclones, leading to an increase in poleward heat transport.

Model simulations evaluated by Abbot et al. (2009) suggest that if the atmospheric carbon dioxide concentration reaches sufficiently high levels (quadrupled), a reduction in winter sea ice, leading to increased heat and moisture fluxes from the ocean surface, may destabilize the atmosphere and promote atmospheric convection. This produces optically thick winter clouds and higher column water vapor content, leading to a stronger longwave radiation flux to the surface, initiating further sea ice loss and, in some models, an ice-free state. Loss of the winter ice cover linked to the convective cloud feedback would lead to a very strong warming of the Arctic. It appears that even with quadrupled carbon dioxide, the winter ice cover cannot be lost in the absence of this feedback.

There is observational evidence for emerging impacts of cloud cover and water vapor on Arctic temperature change. Using satellite data for the period 1979–2004, Francis and Hunter (2006) demonstrate that increases in cloud cover over the Arctic Ocean, more abundant water-containing clouds, and increased water vapor content, have augmented the longwave flux to the surface in spring, which in turn has contributed to northward retreat of the sea ice margin. These interacting processes, which can be viewed as contributing to observed Arctic amplification (Fig. 7), were found to be most prominent over the last decade of the record examined. Screen and Simmonds (2010a) find that part of the recent amplification signal in the cold season over the Arctic Ocean is due to higher water vapor content in the lower troposphere, which is itself a result of having more open water.

3.5. Black carbon aerosols

There is recent evidence of contributions to Arctic warming from aerosols — small liquid or solid particles in the air. Fossil fuel burning has increased aerosol concentrations. There are different types of aerosols. Because they reflect solar radiation, sulfate aerosols have a net cooling effect, partly offsetting warming due to increased concentrations of atmospheric greenhouse gasses. With the advent of cleaner combustion techniques, sulfate aerosol concentrations have declined, but black carbon aerosol concentrations have increased, largely because of increasing emissions from Asia. In contrast to sulfate aerosols, black carbon aerosols strongly absorb solar radiation, and hence have a warming effect on the atmosphere. Results from the modeling study of Shindell and Faluvegi (2009) suggest that the combination of decreasing concentrations of sulfate aerosols and increasing concentrations of black carbon aerosols in the Arctic has substantially contributed to Arctic warming over the past three decades (Fig. 8).

4. The paleoclimate perspective

Paleoclimate records provide ample evidence of Arctic amplification in the past (Brigham-Grette, 2009), even during earlier geologic periods, such as the Cretaceous (65 million years ago) when continental configurations were much different than today. Here we briefly review evidence of past Arctic amplification, drawing strongly from the synthesis of Miller et al. (2010), based on published studies examining temperature proxy records (which tend to be most sensitive to summer temperatures) and results from modeling studies. They focused on the Holocene Thermal Maximum (HTM, about 9000–6000 years ago), the Last Glacial Maximum (LGM), about 21,000 years ago, the Last Interglacial (LIG, or Eemian) about 130,000–120,000 years ago, and the Middle Pliocene warm period, about 3.5 million years ago.

Based on the available evidence, Arctic temperature changes during both warm and cold periods consistently exceed Northern Hemisphere averages by a factor of 3–4. For the HTM, the estimated Arctic summer temperature anomaly compared to the present of +1.7 ± 0.8 °C contrasts sharply with the Northern Hemisphere value of +0.5 ± 0.3 °C. For the LGM, the summer Arctic temperature is estimated to have been −18 ± 7 °C colder than today, compared with −5 ± 2 °C for the Northern Hemisphere. Arctic and Northern Hemisphere anomalies for the LIG are estimated as +5 ± 1 °C and +1 ± 1 °C, respectively. Finally,

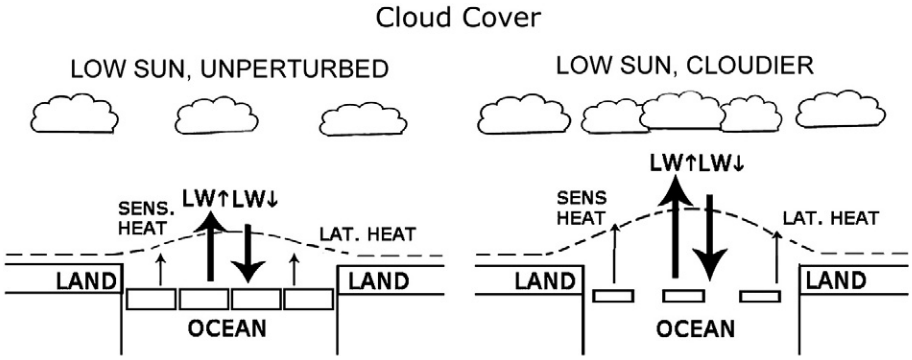

Fig. 7. Schematics of the surface energy budget of the Arctic Ocean, contrasting the situation during the low sun period for (left) an unperturbed Arctic and (right) in response to a forcing that results in more extensive and/or thicker cloud cover. The dotted line is an arbitrary isotherm in the lower troposphere; warming over the Arctic Ocean bows the isotherm upward. Changes in water vapor content linked to changes in open water fraction may contribute to temperature change. SW = shortwave radiation flux, LW = longwave radiation flux, Sens. Heat = sensible heat flux, Lat. Heat = latent heat flux.

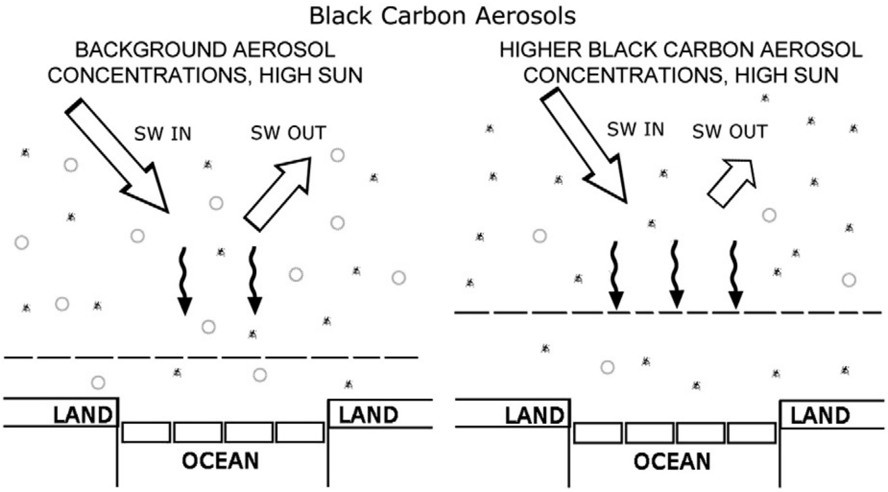

Fig. 8. Schematics of the effects of black carbon aerosols on the absorption of shortwave radiation and resultant emission of longwave radiation by the atmosphere (wavy arrows), contrasting the situation for (left) an Arctic with background aerosol concentrations and (right) with a higher concentration of black carbon aerosols and a lower concentration of sulfate aerosols. The dotted line is an arbitrary isotherm in the lower troposphere; in a warmer atmosphere the isotherm is found at higher level in the atmosphere.

for the middle Pilocene, annual values are estimated as +12°±3 °C for the Arctic and +4°±2 °C for the Northern Hemisphere. These contrasts are summarized in Fig. 9. In an earlier study, Kheshgi and Lapenis (1996) analyzed data for eight warm intervals from the HTM to the Albian (100 Ma) for zonal mean annual temperatures in 10° latitude bands. For 75–85°N, as a ratio of the Northern Hemisphere mean, the values range from 2.4 for the Albian to 3.28 for the Middle Pliocene warm period. The variation of zonal mean temperature anomalies for the HTM shows a curvilinear increase from 30° to 80°N. Increases in zonally-averaged temperatures for the mid-Holocene, Eemian and Middle Pliocene increase from twice the global mean temperature at 60°N to four times the global mean at 80°N.

The key climate forcing associated with the HTM, LGM and LIG is Milankovitch cycles — variations in the eccentricity of the earth's orbit about the sun, axial tilt and precession of the equinoxes. While having only a small effect (less than 0.4%) in solar radiation at the top of the atmosphere averaged for the globe over the year, these variables, acting in combination, strongly affect the seasonal and latitudinal distribution of insolation. For example, at the peak of the HTM, Arctic summer-averaged insolation at 60°N was 32 W m^{-2} greater than at present, and 57 W m^{-2} higher at the height of the LIG. At the LGM, it was 6 W m^{-2} lower (Miller et al., 2010). While such changes in insolation will have direct effects on Arctic climate, they initiate both global and regional-scale processes and feedbacks. Regarding the global scale, it is well established that due to carbon cycle feedbacks, carbon dioxide concentrations were considerably lower than today at the LGM, which along with the high albedo of the ice sheets, largely accounts for the global scale cooling. The cause of the Middle Pliocene warm period is not clear; carbon dioxide levels appear to have been similar to those of today (Pagini et al., 2009).

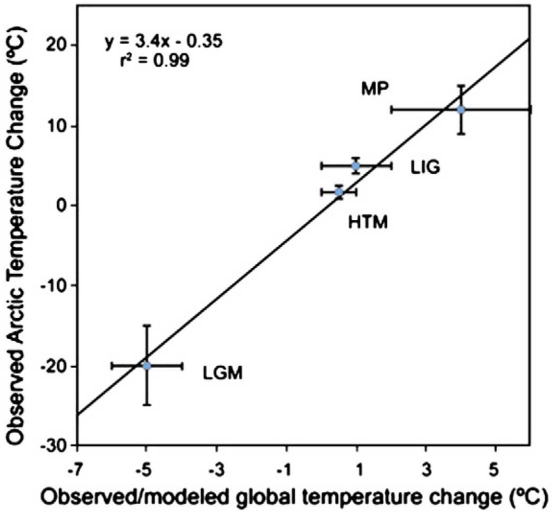

Fig. 9. Paleoclimate estimates of Arctic summer temperature anomalies relative to recent conditions and comparative summer temperature anomalies for the northern hemisphere or globe as a whole (including estimated error bars) for the Last Glacial Maximum (LGM), Holocene Thermal Maximum (HTM), the Last Interglacial (LIG) and the Middle Pliocene (MP). The slope of the regression line indicates that temperature changes are amplified 3–4 times in the Arctic (from Miller et al., 2010).

Sea ice was more extensive at the LGM, which along with the Northern Hemisphere ice sheets, maintained a high albedo helping to keep the Arctic especially cool. The great height of the ice sheets also provided cooling by effectively raising much of the Arctic to a higher level in the atmosphere (Miller et al., 2010). Examined regionally, summer temperature anomalies during the LIG were 4–5 °C and typically +4–6 °C in the Atlantic sector of the Arctic. In Siberia summer temperature anomalies reached +4–8 °C. Peak LIG temperatures at mid- and low-latitudes in the Northern Hemisphere were by contrast only 0–2 °C above present (CAPE, 2006). Part of the Arctic amplification likely relates to having less sea ice. Over land, the snow-covered season would have been shorter than today.

For reasons that remain unclear, there appears to have been a greater dominance of warm Atlantic surface waters around the Arctic during both the LIG and the HTM compared to today (Polyak et al., 2010). Crucifix and Loutre (2002) modeled the transition out of the LIG (126 to 115 ka) using an earth system model of intermediate complexity. Variations in surface albedo due to sea ice growth, snow cover, and vegetation changes were found to nearly quadruple the direct effect of astronomical forcing. The model simulated an annual mean cooling of 5 °C over the northern continents, and up to 14 °C in summer. The strong Arctic warmth during the Middle Pliocene is supported by evidence of widespread forest cover. Summers were likely free of sea ice (Polyak et al., 2010).

5. Impacts

The past decade has seen a growing number of climate modeling studies examining the potential impacts of changes in Arctic sea ice extent on patterns of atmospheric circulation and precipitation. The general approach is to prescribe sea ice extent and/or concentration in the model and then examine how the atmosphere responds to the prescribed conditions. Comparisons between simulations with one set of prescribed ice conditions (e.g., observed extent for the mid 20th century) and another (e.g., expected ice conditions by the middle of the 21st century), while keeping other factors, such as greenhouse gas concentrations, the same, isolates the effect of changing the ice. As discussed earlier, changes in sea ice extent and concentration have strong impacts on temperature that may extend through a considerable depth of the troposphere. During the high sun period, changes in regional albedo are important.

While it comes as no surprise that altering sea ice conditions has impacts on atmospheric circulation, there is little consistency in results from different modeling studies. Some show impacts of reduced ice cover on the location and intensity of the North Atlantic storm track, while others document impacts in the North Pacific sector. Yet others find that impacts are more limited to the Arctic itself (e.g., Alexander et al., 2004; Magnusdottir et al., 2004; Yamamato et al., 2006; Seierstad and Bader, 2008; Higgins and Cassano, 2009; Deser et al., 2010). This in part reflects the use of different models with different experimental designs.

Arctic amplification associated with declining summer sea ice extent may already be influencing atmospheric circulation in the autumn and winter seasons. Due to heat input to the atmosphere, the poleward gradient of 1000–500 hPa thickness has slackened and this has in turn weakened the polar jet stream (Overland and Wang, 2010). Francis et al. (2009) find that autumn sea level pressure fields following summers with less Arctic sea ice extent exhibit positive pressure deviations over much of the Arctic Ocean and North Atlantic, compensated by lower pressures in middle latitudes. The pattern in the North Atlantic is similar to the pattern for the negative phase of the NAO. While an NAO response to reduced sea ice extent is a feature of some modeling studies (e.g., Seierstad and Bader, 2008), as just mentioned results from different studies range widely. Honda et al. (2009) present observational and supporting model evidence that significant cold anomalies in the Far East in early winter and cold anomalies from Europe to the Far East in late winter are associated with the observed decrease in Arctic sea ice extent in the preceding summer and autumn seasons. Simmonds and Keay (2009) argue for a relationship between ice reduction in September and increases in extratropical cyclone intensity, linked to stronger sensible and latent heat fluxes to the atmosphere. While intriguing, this relationship has been questioned (Stroeve et al., 2011).

By contrast, the recent modeling study of Petoukhov and Semenov (2010) provides evidence that recent cold winters over northern continental can be related to forcing by an anomalous decrease in wintertime (not summertime) sea ice extent in the Barents and Kara Seas. Lower tropospheric heating over this region due to the lack of sea ice results in a strong anticyclonic circulation anomaly over the Arctic Ocean and anomalous easterly advection over northern continents, invoking cooling.

Bhatt et al. (2010) show that pronounced warming has occurred along Arctic coasts between 1982 and 2008. The terrestrial warming, argued as a response to removing the regional chilling effect of sea ice and expressed in terms of a summer warmth index, has had an impact on tundra vegetation as demonstrated by increasing values of the satellite-derived Normalized Difference Vegetation Index (NDVI). NDVI represents the fraction of photosynthetically active radiation absorbed by the plant canopy. There has been a 10–15% increase in maximum NDVI along the Beaufort Sea coast of northern Alaska where sea ice concentrations have strongly declined during 1982–2008 (Fig. 10). Note that altered vegetation may itself contribute to Arctic warming through impacts on surface albedo and the sensible heat flux (Foley et al., 1994; Levis et al., 2000).

Experiments with the NCAR Community Climate System Model (CCSM)-3 by Lawrence et al. (2008) suggest that sea ice loss may eventually result in widespread terrestrial warming. As a consequence, the extent of near-surface permafrost by the year 2100 is reduced to only 15% of that in 1970–1989. Of concern is that permafrost thaw will lead to increased microbial activity and release of carbon presently locked up in frozen soils, initiating a feedback to cause further warming.

6. Conclusions

Arctic amplification is an inherent characteristic of the behavior of the Earth's climate system. Arctic amplification over a wide spectrum of temporal and spatial scale scales is evident in the instrumental record, paleoclimatic records, and in climate model projections through the 21st century.

Arctic amplification has a number of known and potential causes. While albedo feedback is often cited as a key driver, albedo feedback is itself a complex process (Curry et al., 1995), having both direct effects on temperature operative during the sunlit season, as well a prominent seasonally lagged effects associated with summer melt of the sea ice cover and heat gain in the ocean mixed layer as dark open water areas are exposed. Different processes can work together. For example, while an increase in atmospheric or oceanic heat flux convergence can increase the temperature, this can lead to reductions in snow cover or sea ice extent that amplify the temperature change. The same can be said of the effects of warming through enhanced concentrations of black carbon aerosols. Changes in heat flux convergence may also lead to changes in atmospheric water vapor and cloud cover that alter the longwave radiation flux to the surface. All of these processes can work in reverse to promote strong Arctic cooling.

What of the Antarctic? Until recently, assessments of Antarctic temperature change over the past several decades emphasized the contrast between strong warming over the Antarctic Peninsula region in austral winter (Fig. 2), and slight cooling over the continental interior (Steig et al., 2009). It has been argued (e.g., Sexton, 2001; Thompson and Solomon, 2002) that stratospheric cooling from springtime ozone depletion has favored the positive phase of the Southern Annular Mode, promoting a generally cool climate and extensive sea ice over most of the coastline, but strong warming over the Peninsula associated with reduced ice extent. However, the link between Antarctic sea ice trends and ozone loss has recently been questioned (Sigmond and Fyfe, 2010). Warming over the interior also seems to be larger previously believed. Using a statistical climate field reconstruction technique that relies on the spatial covariance field of the surface temperature field to guide interpolation from sparse weather station records, Steig et al. (2009) show that significant warming over the period 1957–2006 extends beyond the Antarctic Peninsula to encompass West Antarctica. The ice sheet viewed as whole has seen warming comparable to that for the Southern Hemisphere as a whole.

Most modern climate models nevertheless project that that increases in Antarctic temperature through the 21st century will be smaller than those in the Arctic. In part, this reflects the very different geography of Antarctica; the cold, high elevation Antarctic ice sheet sees little melt at present to support a strong albedo feedback and this will remain true even in a warmer climate. As outlined by Stroeve et al. (2007), surface heat in the southern ocean is rapidly removed from the surface, and hence does not as readily influence the ice cover. The majority of the sea ice is in contact with a near-surface cold-water layer formed by the interaction of a cold katabatic outflow from the continent with coastal water, and this outflow will persist well into the future.

Our synthesis follows on the heels of Serreze and Francis (2006), who examined evidence for Arctic amplification based on observational data through 2003, model output and published studies. At that time, a cold-season warming signal over the Arctic Ocean due to sea ice loss had yet to clearly emerge. The evidence pointed to a preconditioning phase of Arctic amplification, characterized by general warming in all seasons, a lengthening melt season, and an

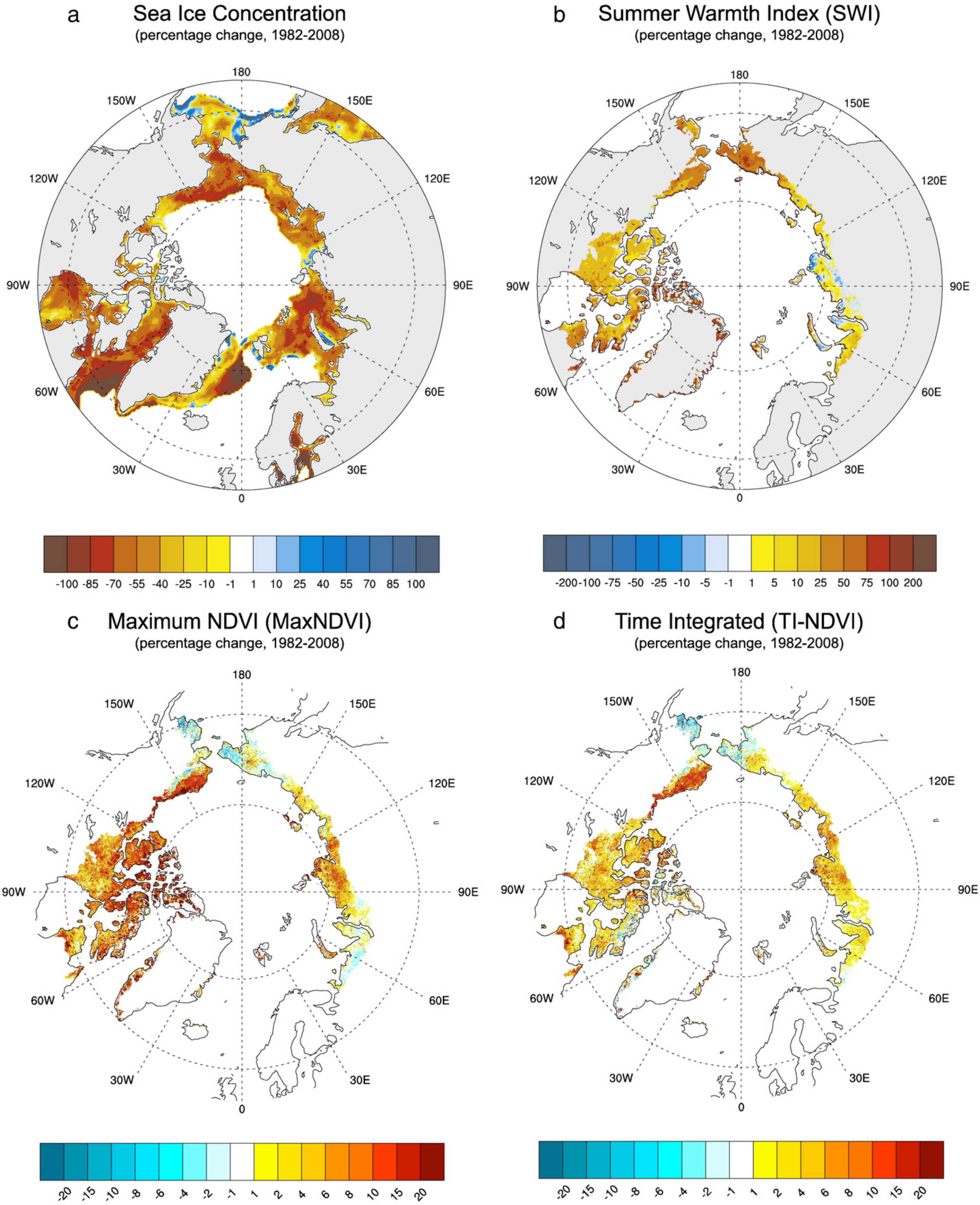

Fig. 10. Percentage change from 1982 to 2008 (the change in the 27 year trend expressed as a percent of the 1982 value) of (a) sea ice concentration at the 50% climatological value, (b) the summer warmth index SWI, (c) MaxNDVI, and (d) TI-NDVI. SWI and NDVI trends are shown only for tundra regions (the southernmost plot latitude is 55°N and color scales are not linear). MaxNDVI is the highest summer NDVI value, and is an indicator of tundra biomass. TI-NDVI is sum of bi-weekly values of NDVI from May to September. The SWI is calculated as the sum of average May through September monthly surface temperatures above the freezing point (from Bhatt et al., 2010).

initial retreat and thinning of sea ice. However, more ice needed to be removed before increases in Arctic Ocean surface air temperatures could unambiguously show the seasonality and magnitudes being projected by models. The awaited signal is now here. While Arctic amplification is expected to become stronger during coming decades, as the sea ice melt-season lengthens and intensifies, spatial and seasonal expression will also be dictated by aerosol loading, soot on snow, changes in oceanic and atmospheric circulation, water vapor, cloud cover and other effects. As we have seen, Arctic amplification may have impacts within the Arctic and beyond, some of which we are only beginning to understand.

Acknowledgments

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