

Arctic Warming Signals from Satellite Observations

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Global warming signals are expected to be amplified in the Arctic primarily because of ice-albedo feedback associated with the high reflectivity of ice and snow that blankets much of the region. The Arctic had been a poorly explored territory basically because of its general inaccessibility on account of extremely harsh weather conditions and the dominant presence of thick perennial ice in the region. The advent of satellite remote sensing systems since the 1960s, however, enabled the acquisition of synoptic data that depict in good spatial detail the temporal changes of many Arctic surface parameters. Among the surface parameters that have been studied using space based systems are surface temperature, sea ice concentration, snow cover, surface albedo and phytoplankton concentration. Associated atmospheric parameters, such as cloud cover, temperature profile, ozone concentration, and aerosol have also been derived.

Recent observational and phenomenological studies have indeed revealed progressively changing conditions in the Arctic during the last few decades (e.g., Walsh et al. 1996; Serreze et al 2000; Comiso and Parkinson 2004). The changes included declines in the extent and area of surfaces covered by sea ice and snow, increases in melt area over the Greenland ice sheets, thawing of the permafrost, warming in the troposphere, and retreat of the glaciers. These observations are consistent with the observed global warming that has been associated with the increasing concentration of greenhouse gases in the atmosphere (Karl and Trenberth 2003) and confirmed by modeling studies (Holland and Bitz, 2003). The Arctic system, however, is still not well understood complicated by a largely fluctuating wind circulation and atmospheric conditions (Proshutinsky and Johnson 1997) and controlled by what is now known as the Arctic Oscillation (AO) which provides a measure of the strength of atmospheric activities in the region (Thompson and Wallace 1998). Meanwhile, the observed Arctic conditions since the 1970s have been shown to exhibit a linear behavior that directly contradicts what has been expected from the AO (Overland, 2005). The decade of the 1990s has been regarded as the warmest decade in the last century and current data indicates that the 2000s may be even a warmer decade than the 1990s further supporting the linear variability. In this paper, we use satellite data to gain insights into the warming Arctic and how the abnormally warm conditions during the last few years are reflected in the region.

Surface Temperature Trends

Among the most important parameters used for monitoring climate change is surface temperature. Historically, surface temperature has been recorded primarily in meteorological stations that had been installed all over the World since the middle of the 19th century. In the Arctic, however, there is a general paucity in the number of stations primarily because of extreme logistical difficulties and the enormous expense of establishing and maintaining such stations. For a more comprehensive coverage of the region, the most practical alternative is through the use of thermal infrared data provided since 1981 by the Advanced Very High Resolution Infrared Radiometer (AVHRR), as discussed in Comiso (2003). It is fortuitous that surface temperature can be conveniently derived in these polar regions since the infrared emissivities of polar surfaces, including those of snow, ice, and water, are spatially uniform and close to unity. Atmospheric effects on the signal are also minimal because the region is relatively arid. Nevertheless, it

should be noted that infrared data provide good surface measurements only during clear sky conditions and therefore, space and time observations over different locations are not uniform. The effect is in part minimized because of the relatively high frequency of observations at high latitudes. Secondly, unambiguous discrimination between cloud covered areas and snow (or ice) covered areas is oftentimes difficult. Special cloud masking techniques have to be applied to minimize associated errors. Thirdly, each AVHRR/infrared satellite sensor has a relatively short lifetime of about 5 years and data from several of these sensors, launched during different time periods, are needed to generate a relatively long time series. We use in situ data to check the consistency of the radiances from the different AVHRR satellite sensors and to improve the calibration of each sensor.

The general spatial distribution of temperature isotherms in the Arctic region can be inferred from the color-coded map in Fig 1a. This map represents the overall average of the monthly AVHRR surface temperatures from August 1981 to July 2005 and is referred to as the satellite climatology of the Arctic. The image provides a convenient means of identifying regions of interest, including locations of extremely cold temperatures in Greenland, Northern Canada, Siberia, and the North Pole region. The basic monthly images (not shown), which are gridded at a resolution of 6.5 by 6.5 km, are coherent with each other and reflect the expected changes from one season to another. To assess how the Arctic surface temperature has been changing, the average value of each data element for the first half of the time series (August 1981 to July 1993) is subtracted from the corresponding average for the second half of the series (August 1993 to July 2005) and the results are shown in (Fig. 1b). The change map shows a predominance of positive values in the Western Arctic, North America, Greenland and much of Europe. Surprisingly, there are considerable areas of negative changes generally located in Russia. Linear regressions were done on each data element using monthly anomaly data from 1981 to 2005 and the slopes are used to represent the trend in temperature per decade as shown in Fig. 1c. The patterns in this trend map are similar to those in the difference map with the positive (and negative) trends in the same general areas where the positive (and negative) differences are located. The changes depicted in Figs. 1b and 1c are not of the same magnitude in part because one represents a 12-month average change while the other represents a decadal (10-year) trend. The areas of negative and positive trends have been compared with those from in-situ data (Comiso 2003) at locations where the latter are available and the results show good agreement. The overall trend of data inside 60° N is 0.72 ± 0.10 °C decade⁻¹, while regionally, it is 0.54 ± 0.11 °C decade⁻¹ over sea ice, 1.19 ± 0.20 °C decade⁻¹ over Greenland, 0.84 ± 0.18 °C decade⁻¹ over North America and 0.13 ± 0.16 °C decade⁻¹ over Northern Eurasia. It is apparent that significant warming has been occurring in the Arctic surface temperature but not uniformly from one region to another.

To illustrate how the early years compare with the more recent years, yearly anomalies in 1982, to 1985 are presented side by side with corresponding anomalies in 2002 to 2005 (Fig. 2). Each yearly anomaly was derived by subtracting the climatology (i.e., Fig. 1a) from the yearly-average temperature. The yearly data are averages from August of one year and to July of the following year to allow for the assessment of temperature changes over different sea ice (growth and decay) seasons. It is apparent that negative anomalies are a lot more prevalent in the 1980s compared to those in the 2000s. The aforementioned negative trend in the Russian region at about 90°E (Fig. 1c) is likely caused by the positive anomalies in the region in the 1980s and the negative anomalies in the same region in the 2000s. The anomaly maps show large spatial and interannual changes demonstrating overall warming but at the same time a very complex Arctic system.

Strong Signals from the Perennial Sea Ice Cover

The most remarkable warming signal in the Arctic to date as observed using satellite data is arguably, the rapidly declining perennial sea ice cover, as reported previously (Comiso 2002). The relatively long time series of sea ice cover data used in this study and to generate the climatology were derived from data provided by the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the DMSP/Specially Scanning Microwave Radiometer (SSM/I). Since that report, we have had four consecutive years, (i.e., 2002, 2003, 2004, and 2005) when the extent and area of the Arctic perennial ice cover were abnormally low as shown in Figure 3. For optimum resolution, the maps shown were derived from the Advanced Microwave Scanning Radiometer which was launched on board EOS/Aqua (AMSR-E) on 4 May 2002. The images were gridded at a resolution of 12.5 by 12.5 km compared to 25 by 25 km used in the standard data set that provides the climatology. The ice free ocean is shown in blue while the climatological ice cover (average of all monthly data from November 1978 to July 2005) with concentration of at least 15% is shown in gray. During the period of overlap (June 2002 to the present), the SSM/I and AMSR-E data have been shown to provide almost identical results. The areas covered by gray in the maps represent basically the magnitude of the change in the perennial ice cover when compared with each of the last four years. The most vulnerable area for the perennial ice cover had been the Beaufort/Chukchi Sea region where the area of melted sea ice in this region reached what was then a record high in 1998. Since that year, the extent of the open ocean in the region stayed high compared to climatological value except for a minor rebound in 2001. In 2005, however, the area of open water has shifted to the east with the Beaufort Sea not as wide open as in the previous three years. This represents a recovery in the Beaufort Sea region but this may not mean much because of ocean dynamics and constantly changing wind circulation.

To better illustrate the evolution of the Arctic perennial ice cover, 5-year averages of the daily ice extent and ice area during the summer and autumn are presented in Figs. 4a and 4b, respectively. The five-year-average plots show what is not apparent in the yearly plots and indicate progressively lower values almost every ten years. They also indicate a phase shift from earlier years to more recent years suggesting delays in the onset of growth period for the latter and making it more unlikely for the ice cover to recover its previous thickness. Also plotted are the corresponding daily values for 2005 and 2002 ice cover which indicate large departures of the from the 5 year averages. It is apparent that the 2005 data show abnormally low values during August indicating fast decline of the seasonal ice but the minimum values, representing the perennial ice cover, are only slightly lower than that of the previous low record value in 2002.

The maximum yearly values of the ice extent and area during the winter period (Fig. 5a) are shown together with the minimum values at the end of the melt season (Fig. 5b). The ice cover during maximum extent represents the perennial ice cover from the previous year plus the seasonal ice cover during its peak value while the minimum extent represents the winter ice cover that survives the summer melt (i.e., perennial ice). The yearly winter maximum ice area is shown to be much more stable than the yearly minimum ice cover with the yearly variation in the former being less than 10^6 km^2 while that of the latter being as large as $2 \times 10^6 \text{ km}^2$. It is remarkable that the estimated trend for the ice area during the winter maxima is only about -1.6 % per decade while that of the summer minimum is about -9.6 % per decade. Such a big difference in the trend is especially intriguing since modeling studies have indicated that the warming induced by greenhouse gases is expected to be most apparent during the winter period in the Arctic because of the dominant influence of long wave radiation during this period.

The much more negative trend of the ice cover during summer minima compared to that during winter maxima may be an indication that the effect of the warming in winter is not observed in the ice cover until the summer season. It is apparent, however, that the relationships of the high and low values are not always intuitively consistent. In the 1980s, high values in the winter maximum (e.g., 1983 and 1988) led, as expected, to high values in the perennial ice, but this was not the case in the 1990s (e.g., 1990 and 1998). Similarly, low values in the winter maximum (e.g., 1981 and 1984) usually led to low values in the perennial ice in the 1980s, but low values (e.g., 1996) led to high values in the 1990s. Furthermore, a high perennial ice cover in one year does not always lead to high maximum ice areas the following winter. The much larger yearly fluctuations in the 1990s than in the 1980s also leads to a higher fraction of the relatively thin second year ice in the perennial ice cover and hence, thinner ice overall in the 1990s than previous years, as pointed out by Comiso (2002). The anomalies in the ice cover in the 1990s have been explained in terms of an observed shift in the indices of the Arctic Oscillation, starting in 1989 (Rigor et al. 2002; Lindsay 2005). Such a shift in what is supposedly a predictable cycle only illustrates the complexity of the climate system and the poorly understood intricacies in the interactions of the ice cover with various environmental variables such as surface temperature, wind circulation, ocean dynamics and cloud cover. Although we don't know for sure why the perennial ice cover were extremely low 4 years in succession and for 7 of the last 8 years, this phenomenon is consistent with the aforementioned warming of the Arctic (see Figs 1 and 2) and the expected positive ice-albedo feedback from the previously observed ice decline (Comiso 2002).

Changing Melt Patterns and Albedo

Unique to the polar regions is the ever presence of sea ice, glaciers, permafrost, snow and ice sheets that are highly sensitive and vulnerable to above freezing (i.e., melt) temperatures. The overall impact of temperature on these surfaces depends on the actual magnitude and the length of the melt period. If the duration is short, the impact may be minimal, but if it is long enough, the surface can undergo drastic changes. For example, thick multiyear ice floes usually survive the summer melt period and could regenerate its volume during the subsequent winter. However, an unusually warm summer and a long period of melt could cause a multiyear ice floe to completely turn to liquid and becomes part of the aforementioned decline in the perennial ice cover.

The satellite AVHRR data provide the means to evaluate directly the changing melt patterns in the various Arctic surfaces. Using a technique described by Comiso (2003), the lengths of melt period in various polar areas have been changing significantly during the last few decades. Updating previous results, the length of melt has been estimated to be increasing by 15.2, 1.5, 2.0, 5.5 days decade⁻¹ over sea ice, the Greenland ice sheet, Northern Eurasia and northern North America, respectively. The results indicate that the sea ice cover is subject to almost a month longer of melt season at present than in 1979. Such an increase in melt period would cause sea ice to be thinner (Hakkinen and Mellor 1990) and in part explain why the perennial ice cover is declining.

The effect of warming on the Greenland ice sheet can be very profound since previous studies had indicated that a complete melt of the ice sheet would cause the sea level to rise by as much as 7 meters, assuming isostatic adjustments during deglaciation. The aforementioned positive increase in the melt period in Greenland is consistent with the observed thinning of the ice sheet

in various places, especially near the coastal areas (Krabill et al. 2000). The melt area as previously inferred using satellite passive microwave data and has been reported to have large interannual variability in recent years (Abdalati and Steffen 1997; Zwally and Fiegles 1994). An abnormally large melt area in 2002 has been reported (Koni Steffen private communication, 2004) using the same technique. Passive microwave systems provide surface information at a good time resolution because of minimal effects of cloud cover on the data. But the footprints are large and the melt signature varies with the degree of wetness affecting the accuracy of the melt algorithm. For comparative analysis, we use AVHRR surface temperature data to study the same phenomenon. Although satellite infrared data do not have the same time resolution, it provides direct measurements of temperature and could provide insights into the melt processes in the region. Using infrared data, the yearly melt area is determined by taking the sum of all the data elements within the ice sheet in which melt temperature was reached at least in one weekly average. The results for each year from 1982 to the present are presented in Figure 6a. As shown, the percentage area of melt was anomalously high in 2002 and has only slightly recovered since with the values being very high again in 2005. For comparison, the corresponding percentage for areas in which melt occurred in at least two weeks were also estimated as shown in Fig. 6a (in red) indicating a more gradual increase during the last 4 years. With a simple regression analyses, the trend for the percentage melt area with less than one week melt period is 3.8 % per decade while that with less than two weeks melt period is 2.6 % per decade. What is remarkable is that the area of melt was basically constant until 2002 when the area of melt increased considerably from the previous average value. The big increase in 2002 is not apparent in the two-week data because the extensive melt in 2002 occurred for only about a week. Similar studies have been done using passive microwave data by Abdalati (this volume). The two studies are generally consistent with the peaks and dips occurring at about the same time. The magnitudes of the changes are not identical partly because of the differences in both spatial and temporal resolution and partly because of different sensitivity to the surface of the two data sets.

The average length of melt is a parameter that is useful for evaluating the state of other surfaces. To illustrate how the data can be used to study the impact of warming in different regions, length of melt data in 1982 and 2002 are shown in Figs. 7a and 7b, respectively. The maps show the boundary of continuous permafrost (red line) and also of discontinuous permafrost (in blue line). It is apparent that there is significant difference, not just over the Greenland ice sheet and sea ice but also in other Arctic regions. To be able to assess the change more quantitatively, the difference of data in Figs. 7a and 7b are presented in Fig. 7c. The changing length of melt over the permafrost areas including large parts of Alaska, North America and Eurasia are shown to be vulnerable to change on account of increases in the length of melt period. Using climatology as baseline, areas that are severely affected by melt can be assessed on a year by year basis. North of the boundary of continuous permafrost are also areas where thousands of glaciers in the Arctic are located. Northern Canada is the location of hundreds of them, especially in the Queen Elizabeth Islands. It is apparent that the length of melt in the Ellesmere Island has been increasing. Such increase would in part explain observed declines in glacier areas (Abdalati this volume).

The changing ice and snow conditions can affect the albedo of the Arctic in a big way. With the ice-albedo feedback being the key contributor to the amplification of global climate signal, it is important to assess how the surface albedo has been changing. To provide insights into the extent and magnitude of the change, monthly averages of the 0.51 μm albedo derived from one of the AVHRR channels have been generated from 1981 to the present. The averages for the entire

Arctic region during the first and last 12 months of the data as well as the difference are shown in Figs. 8a, 8b, and 8e. The difference data indicate negative changes mainly in the sea ice region and almost no change in land areas. The corresponding averages using only the September monthly data are also shown in Figs. 8c, 8d, and 8f. The September difference maps show considerable negative change in the Beaufort and Chukchi Seas where the perennial ice has been retreating considerably. Negative changes are also observed in North America Greenland and Europe while negative changes are apparent in Russia. Overall, the retreat of the perennial ice cover represents the biggest change in albedo.

Discussions and Conclusions

Satellite infrared data reveal that since 1981, the Arctic region has been warming at a high rate of 0.72 ± 0.10 °C per decade inside the Arctic circle and 0.65 ± 0.08 °C for the region $> 60^\circ\text{N}$. It is apparent that negative anomalies are quite dominant during the 1980s compared to the 1990s and the 2000s with the years from 2002 to 2005 being unusually warm. The perennial ice cover has been anomalously low consistently during the last 4 years and in 7 of the last 8 years. The updated trend in the Arctic perennial ice cover is now 9.6 % per decade, compared to the previous estimate of 8.9% per decade. The average area of the perennial ice from 2002 to 2005 was 4.95×10^6 km² while the corresponding value from 1979 to 1982 was 6.33×10^6 km² yielding a difference of 1.38×10^6 km² or a decline of 9.9% per decade. Large interannual variability in the perennial ice area was also observed in the 1990s compared to the 1980s suggesting increases in the fraction of the thinner second year ice during the latter period that may explain the observed thinning from one period to another.

The lengths of melt periods have also been quantified and estimated to be increasing at varying rates over sea ice, the Greenland ice sheet, Northern Eurasia and northern part of North America, respectively, inside 60° latitude. The enhanced melt period over sea ice may in part explain why the perennial ice cover has been decreasing. The change over Greenland and Northern America is also alarming in part because it implies the vulnerability of the ice sheet and thousands of glaciers in the North. The yearly area of melt at the Greenland ice sheet has been relatively stable until 2002 when there was a drastic increase and has not recovered since. The rate of increase in the area of melt regions is estimated to be around 3.8% per decade. The length of melt period is also examined in other parts of the Arctic, especially in Northern Canada and Alaska where the trends in surface temperature are 0.86 ± 0.24 and 0.83 ± 0.20 °C per decade. These regions are locations of thousands of glaciers and such increases in temperature makes them very vulnerable.

The visible channel of the AVHRR data also indicate a declining albedo in the Arctic but mainly in the sea ice region and during the summer. The rate of change is not significant over land areas and the decline in the sea ice region in September is associated mainly with the observed decline in the perennial ice cover.

The changes observed by satellite data is unprecedented in terms of coverage and temporal resolution. But the data record is so far only around 25 years and the results presented may not be long enough to capture some of the longer term variabilities that are inherent in the complex climate system. However, with time, such data will become more and more crucial not only in verifying predictions of climate models but also in establishing the baseline that will be used in assessing accurately how our climate has been changing.

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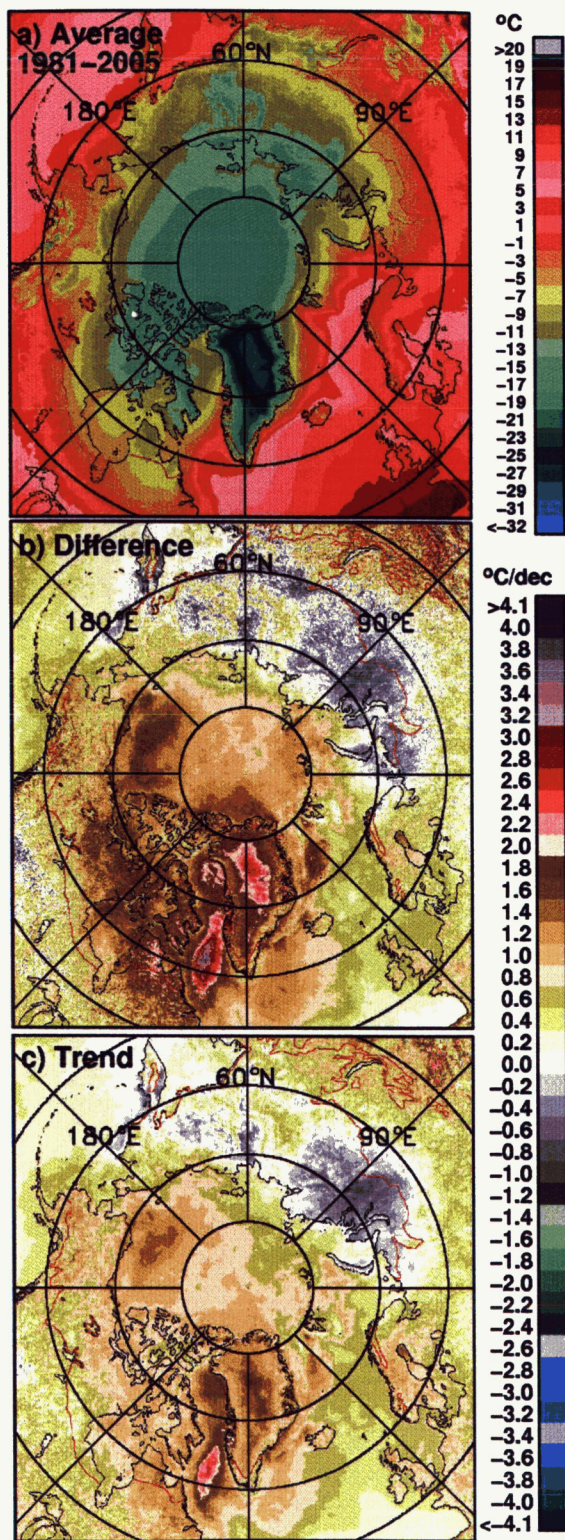


Figure 1

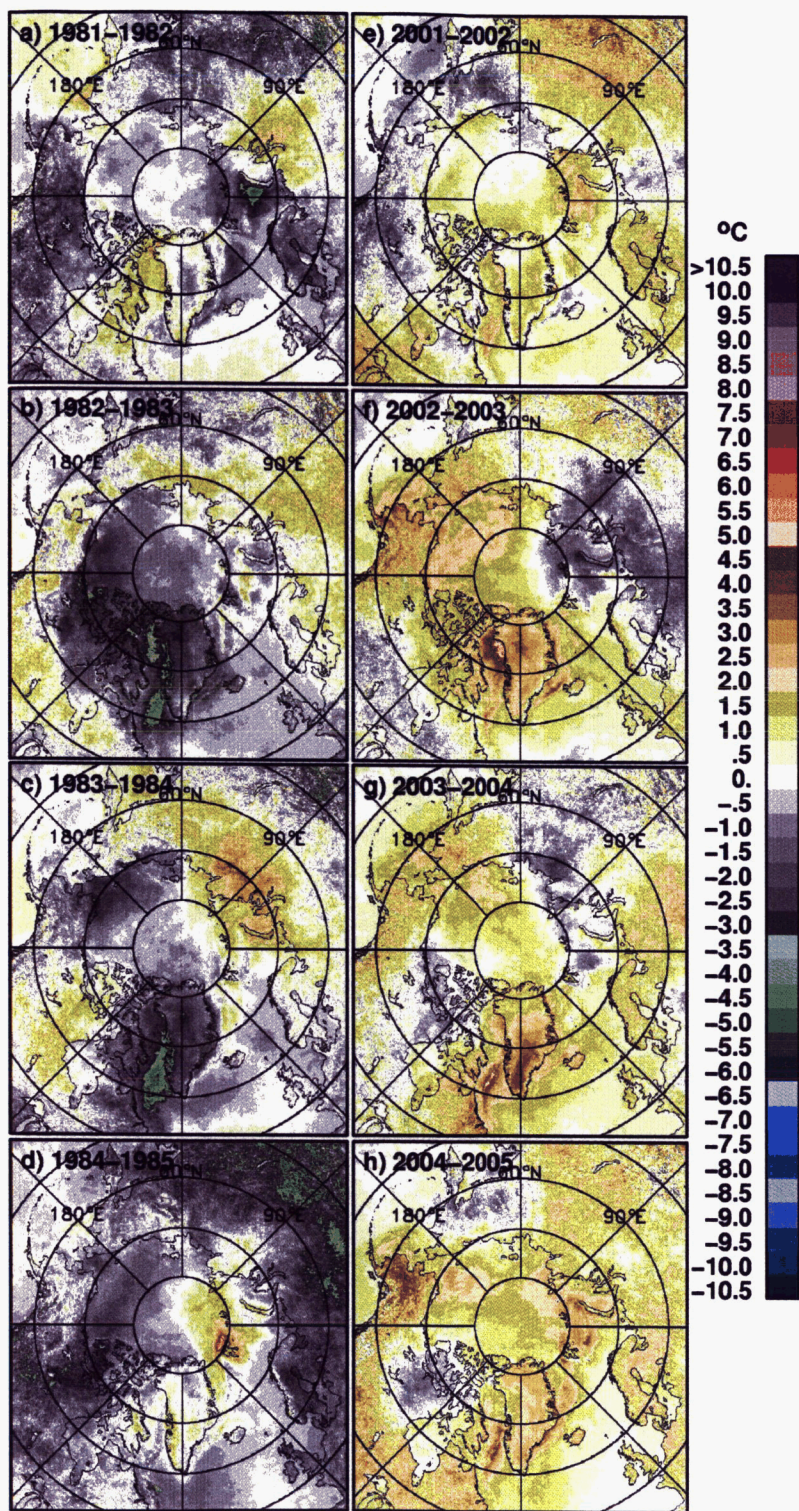


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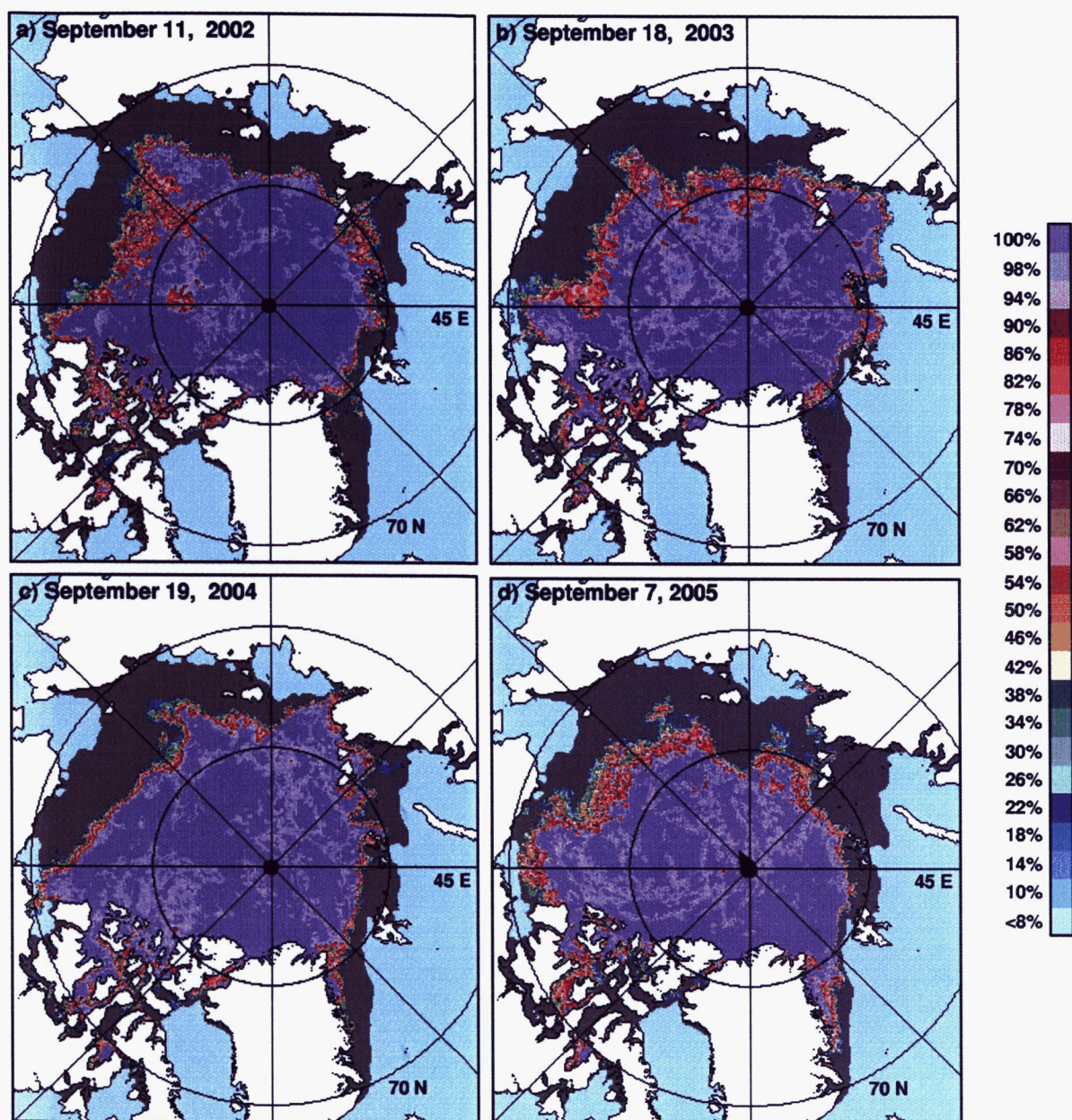


Figure 3

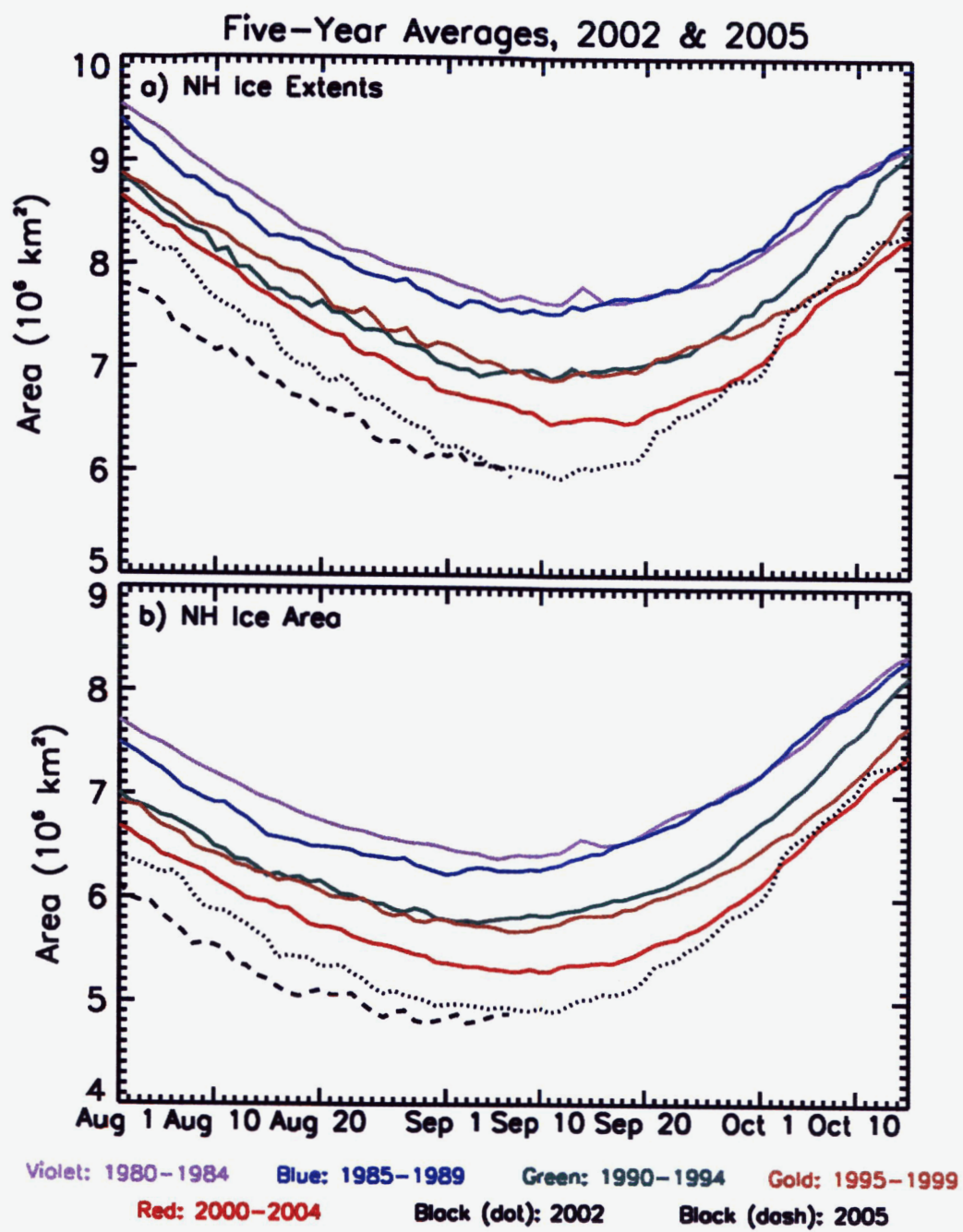


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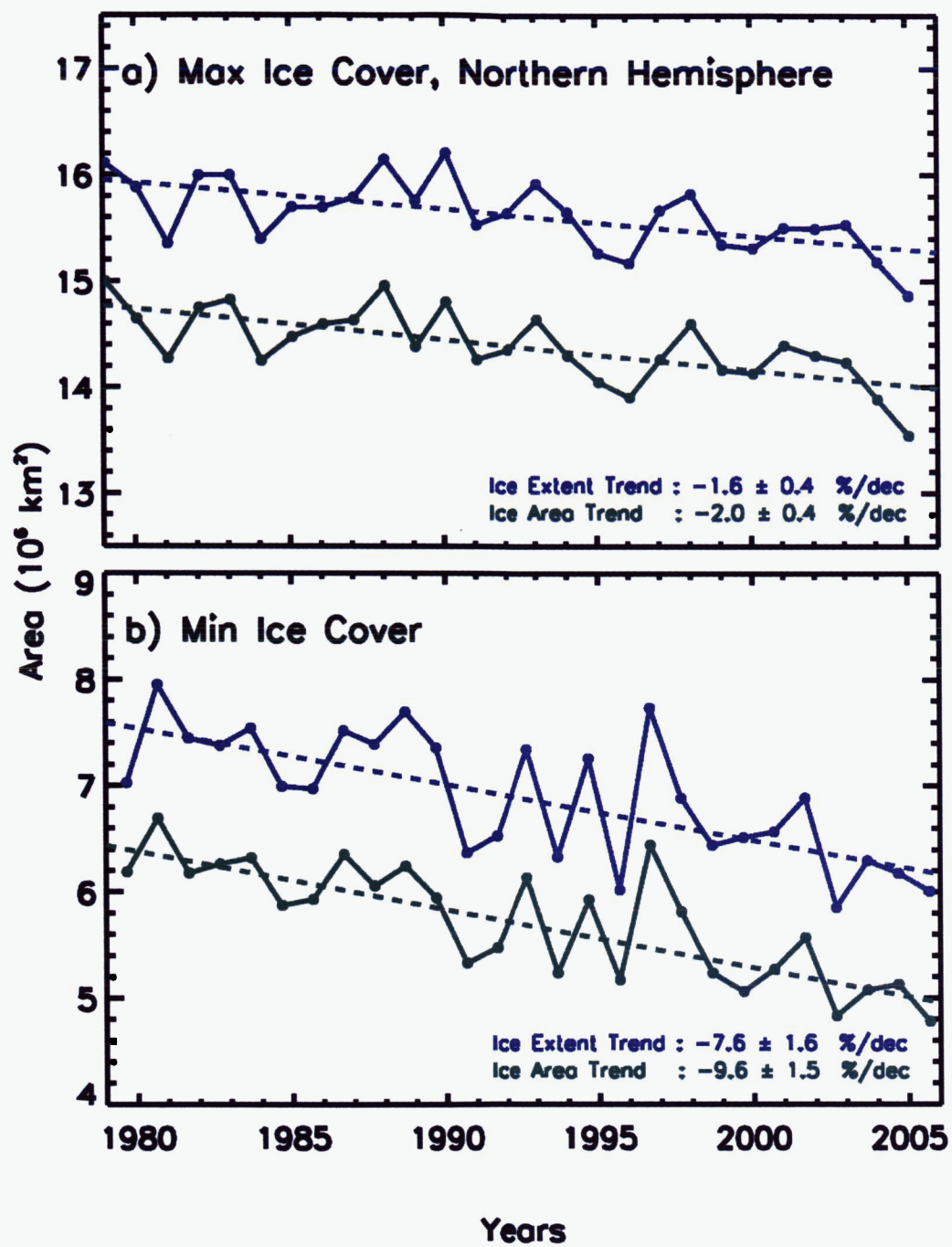


Figure 5

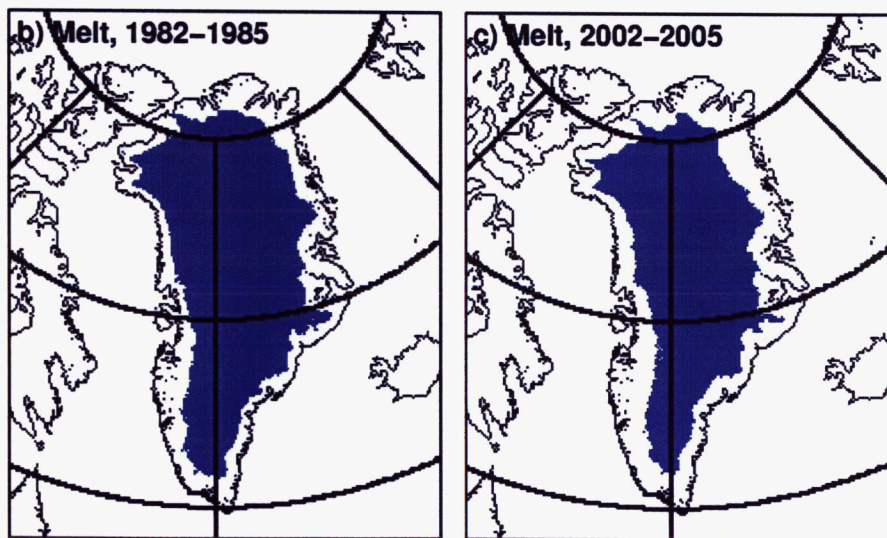
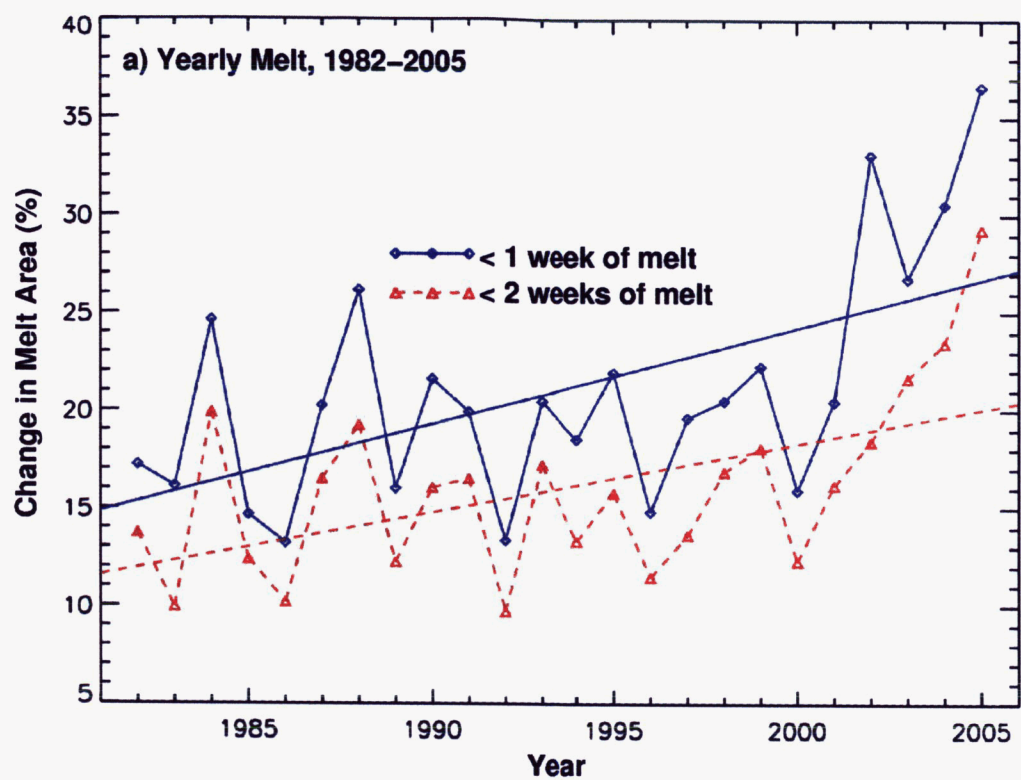


Figure 6

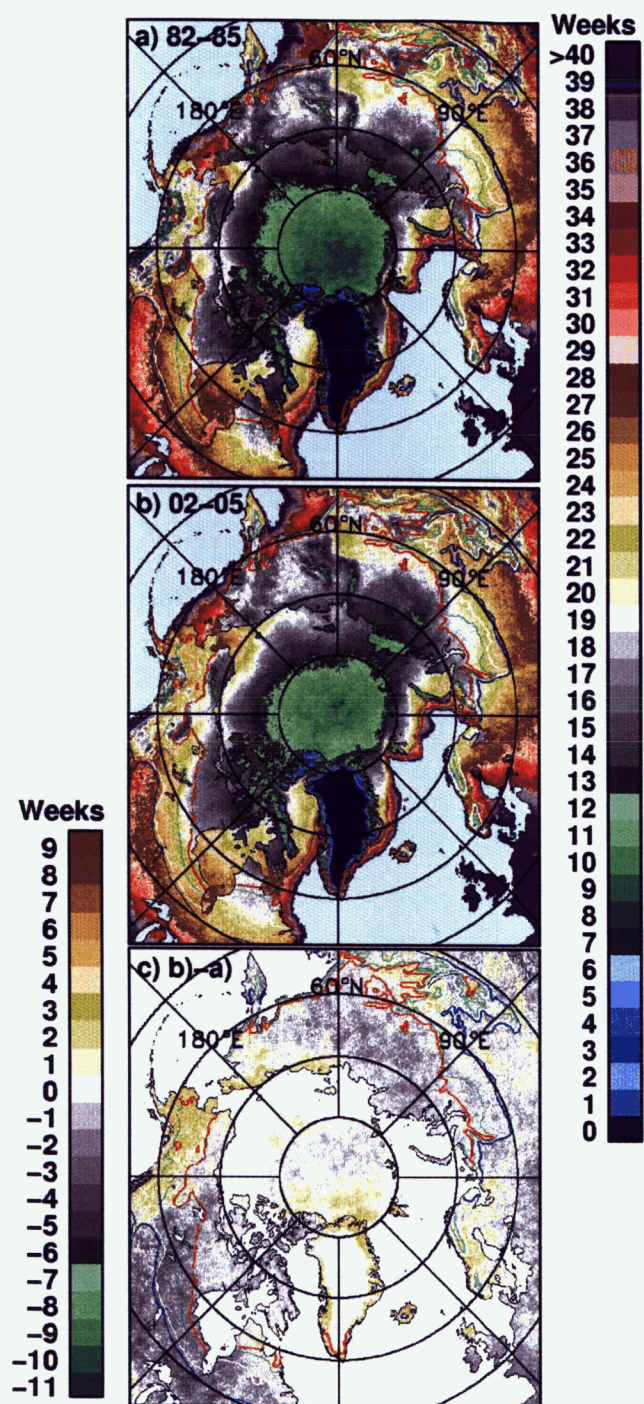


Figure 7

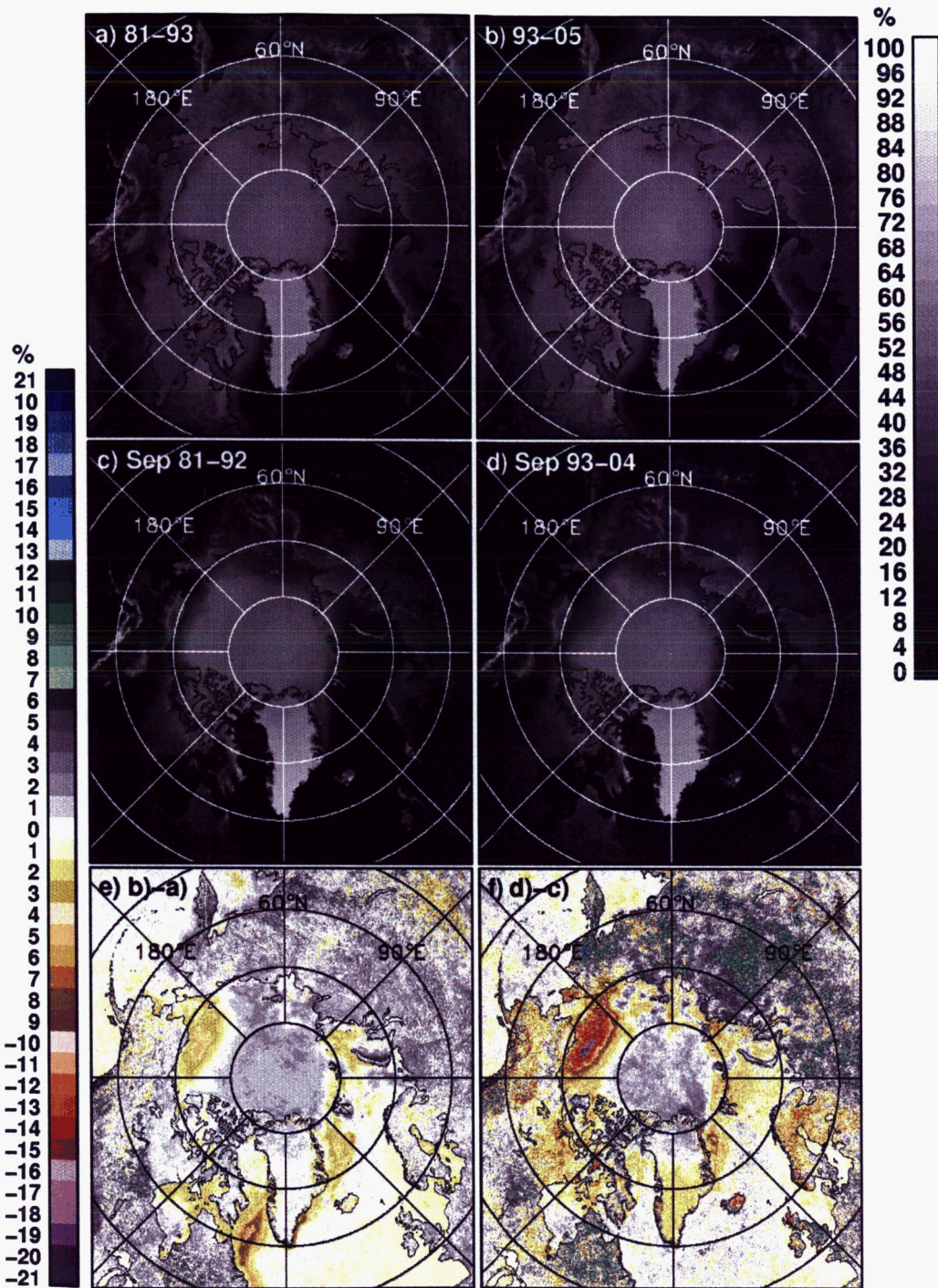


Figure 8

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Abstract:

Satellite infrared data reveal that since 1981, the Arctic region has been warming at a high rate of 0.72 ± 0.10 °C per decade inside the Arctic circle and 0.65 ± 0.08 °C for the region $> 60^\circ\text{N}$. It is remarkable that during about the same period, the Arctic perennial ice cover has been declining at a rapid rate of 9.6 % per decade. The perennial ice cover has been anomalously low consistently during the last 4 years and in 7 of the last 8 years. The average area of the perennial ice from 1979 to 1982 was 6.33×10^6 km² while the corresponding value from 2002 to 2005 was 4.95×10^6 km² indicating a loss of about 1.38×10^6 km². Large interannual variability in the perennial ice area was also observed in the 1990s compared to the 1980s suggesting increases in the fraction of the thinner second year ice during the latter period that may explain the observed thinning from one period to another. The lengths of melt periods have been quantified using surface temperature data and estimated to be increasing at varying rates over sea ice, the Greenland ice sheet, Northern Eurasia and the northern part of North America, respectively, inside 60° latitude. The largest increase in melt period is observed over sea ice at about 15 days per decade which may in part explain why the perennial ice cover has been decreasing. The yearly area of melt at the Greenland ice sheet has been relatively stable until 2002 when there was a drastic increase and has not recovered since causing an overall rate of increase of 3.8% per decade in the area of melt region. The length of melt period is also examined in other parts of the Arctic, especially in Northern Canada and Alaska where the trends in surface temperature are 0.86 ± 0.24 and 0.83 ± 0.20 °C per decade. These regions are locations of thousands of glaciers and permafrost and such increases in temperature make the latter very vulnerable. The visible channel data of the AVHRR sensor also indicate that the average albedo in the Arctic is declining, especially in the sea ice region and during the summer. A recovery for perennial ice cover would require a sustained cooling period but with the ice-albedo feedback and the observed warming trend, this may not happen soon.

Popular Summary

Global warming signals are expected to be amplified in the Arctic primarily because of ice-albedo feedback associated with the high reflectivity of ice and snow that blankets much of the region. Indeed, satellite infrared data reveal that since 1981, the Arctic region has been warming at a high rate of 0.72 ± 0.10 °C per decade inside the Arctic circle and 0.65 ± 0.08 °C for the region $> 60^\circ\text{N}$. Concurrently, it is remarkable that the Arctic perennial ice cover has been declining at 9.6 % per decade using passive microwave data. The perennial ice cover, which is the mainstay of the Arctic sea ice cover and consist primarily of thick multiyear ice floes, has been anomalously low consistently during the last 4 years and in 7 of the last 8 years. The average area of the perennial ice from 1979 to 1982 was 6.33×10^6 km² while the corresponding value from 2002 to 2005 was 4.95×10^6 km² yielding a significant difference of 1.38×10^6 km². Large interannual variability in the perennial ice area was also observed in the 1990s compared to the 1980s suggesting increases in the fraction of the thinner second year ice during the latter period that may explain the observed thinning from one period to another.

The lengths of melt periods have also been quantified and estimated to be increasing at varying rates over sea ice, the Greenland ice sheet, Northern Eurasia and northern part of North America, respectively, inside 60° latitude. The increase in melt period is largest over sea ice at about 15 days per decade which may in part explain why the perennial ice cover has been decreasing. The yearly area of melt at the Greenland ice sheet has been relatively stable until 2002 when there was a drastic increase and has not recovered since causing an overall rate of increase of around 3.8% per decade in the area of melt. The length of melt period is also examined in other parts of the Arctic, especially in Northern Canada and Alaska where the trends in surface temperature are 0.86 ± 0.24 and 0.83 ± 0.20 °C per decade. These regions are locations of the permafrost and thousands of glaciers and such increases in temperature would make them very vulnerable. The AVHRR visible channel data also indicate a decline in the overall albedo of the Arctic surface which is most pronounced during the summer at the peak of solar insolation. It will take a sustained cooling period, especially during the summer, for the perennial ice cover to recover but because of ice-albedo feedback and the observed warming trend, this may not happen soon.

The changes observed by satellite data in the Arctic are considerable and are unprecedented in terms of coverage and temporal resolution. But the data record is so far only around 25 years and the results presented may not be long enough to capture some of the longer term variabilities that are inherent in the complex Arctic climate system. However, with time, such data will become more and more crucial not only in verifying predictions of climate models but also in establishing the baseline that will be used in assessing accurately how our climate has been changing.

Significant Findings

This paper reports four very important phenomena that has been observed from space borne sensors: (1) the Arctic region has been warming at a high rate of 0.72 ± 0.10 °C per decade inside the Arctic circle and 0.65 ± 0.08 °C for the region $> 60^\circ\text{N}$ since 1981; (2) the Arctic perennial ice cover has been declining at 9.6 % per decade since 1979; (3) melt period over the Arctic has been increasing over sea ice and land; and (4) the albedo of the Arctic is decreasing, especially in the summer. The most remarkable of these findings is likely the rapid decline of the perennial ice cover which has been anomalously low consistently during the last 4 years and in 7 of the last 8 years. The average area of the perennial ice from 1979 to 1982 was 6.33×10^6 km² while the corresponding value from 2002 to 2005 was 4.95×10^6 km² indicating a big decrease of 1.38×10^6 km². Large interannual variability in the perennial ice area was also observed in the 1990s compared to the 1980s suggesting increases in the fraction of the thinner second year ice and overall thinning of the ice during the latter period. The lengths of melt periods have also been quantified and estimated to be increasing at varying rates over sea ice, the Greenland ice sheet, Northern Eurasia and northern part of North America, respectively, inside 60° latitude. The increase in melt period is largest over sea ice at about 15 days per decade and this in part may explain why the perennial ice cover has been decreasing. The yearly area of melt at the Greenland ice sheet has been relatively stable until 2002 when there was a drastic increase and has not recovered since causing an overall increase rate in the area of melt regions at around 3.8% per decade. The length of melt period is also examined in other parts of the Arctic, especially in Northern Canada and Alaska where the trends in surface temperature are 0.86 ± 0.24 and 0.83 ± 0.20 °C per decade. These regions are locations of thousands of glaciers and such increases in temperature make them very vulnerable. The visible channel of the AVHRR data also indicate a declining albedo in the Arctic but mainly in the sea ice region and during the summer. The rate of change is not so significant over land areas when yearly averages are used but the September data indicate more substantial changes, especially that associated with the observed decline in the perennial ice cover.