Title: "Impact Studies of a 2° C Global Warming on the Arctic Sea Ice Cover"

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1. Abstract

The possible impact of an increase in global temperatures of about 2°C, as may be caused by a doubling of atmospheric CO_2, is studied using historical satellite records of surface temperatures and sea ice from late 1970s to 2003. Updated satellite data indicate that the perennial ice continued to decline at an even faster rate of 9.2 % per decade than previously reported while concurrently, the surface temperatures have steadily been going up in most places except for some parts of northern Russia. Surface temperature is shown to be highly correlated with sea ice concentration in the seasonal sea ice regions. Results of regression analysis indicates that for every 1°C increase in temperature, the perennial ice area decreases by about 1.48 x 10^6 km^2 with the correlation coefficient being significant but only -0.57. Arctic warming is estimated to be about 0.46°C per decade on average in the Arctic but is shown to be off center with respect to the North Pole, and is prominent mainly in the Western Arctic and North America. The length of melt has been increasing by 13 days per decade over sea ice covered areas suggesting a thinning in the ice cover. The length of melt also increased by 5 days per decade over Greenland, 7 days per decade over the permafrost areas of North America but practically no change in Eurasia. Statistically derived projections indicate that the perennial sea ice cover would decline considerably in 2025, 2035, and 2060 when temperatures are predicted by models to reach the 2°C global increase.

2. Popular Science Summary

Global warming in the Arctic is to a certain degree already manifested by observed retreat of the snow cover, melt of glaciers, thawing of the permafrost and decline of the sea ice cover. Satellite data have also revealed a rapidly retreating perennial sea ice cover during a time period when the Arctic surface warmed up by about 1°C. But it is remarkable that more recent ice cover data show decreases at an even more rapid phase with the three least extensive perennial ice cover occurring in 2002, 2003 and 2004. An update of data used in previous reports shows that the perennial ice cover is now declining at a rate of 9.2 % per decade (compared to 8.9% previously reported) while the surface temperature has been steadily going up in most places except parts of northern Russia. It is also apparent that the most rapid retreat in the perennial ice cover has been occurring in the Beaufort and Chukchi Seas while warming is going on in adjacent regions, including North America and Greenland. The length of melt patterns, however, appears to be more symmetrical with the North Pole as the central area and progressively increase to the south except in Greenland and glacier areas. The length of melt, which has been shown to be sensitive to the thickness of the sea ice cover, is observed to be increasing at an alarming rate of 13.1 days per decade over sea ice covered regions. It is also increasing at the rate of 4.3 and 5.3 days per decade in Greenland and the permafrost regions of North America while the change is negligible over the permafrost regions of Eurasia. Results of linear regression analysis suggest that for every 1°C increase in surface temperature, the area of the perennial ice cover decreases by about

1.48×10^6 km^2. The correlation of the two variables is, however, not very high with the correlation coefficient being only 0.57 but this is not totally unexpected. Using statistical techniques, currently observed distribution of the perennial ice cover is projected into the years 2025, 2035, and 2060, when a 2°C global warming is expected to occur, and the results show ever increasing open ocean areas in the Beaufort, Siberian, Laptev and Kara Seas. The impact of such a largely increasing open water area could be profound and could mean changes in the ocean circulation, marine productivity, ecology, and the climate of the region. The simple linear model used for projecting the ice cover is likely too simplified but the results appear to provide a good representation of the future on a near term and may avail useful insights into the changing Arctic ice cover. The technique does not allow for the sea ice cover to rebound, which is a possibility, especially on inter-decadal periods because of AO and NAO. However, if the trend continues, the ice-albedo feedback effects would dominate, as may already be occuring, and the projections would provide us with a good idea on how the perennial ice would be like when a doubling in the atmospheric CO_2 concentration occurs.

3. Significant Findings:

Satellite record from late 1978 through 2003 indicate that the perennial ice continued to decline at an even faster rate of 9.2 % per decade than previously reported while concurrently, the surface temperatures have steadily been going up in most places except for some parts of northern Russia. Surface temperature is shown to be highly correlated with sea ice concentration in the seasonal sea ice regions. Results of regression analysis indicates that for every 1 °C increase in temperature, the perennial ice area decreases by about 1.48×10^6 km^2. This is a useful relationship but the correlation of the two variables is not very strong, the correlation coefficient being only -0.57. Arctic warming is estimated to be about 0.46°C per decade on average but is shown to be off center with respect to the North Pole, and is prominent mainly in the Western Arctic, Greenland and North America. The length of melt has been increasing by 13 days per decade over sea ice covered areas, including those that melt completely in the summer. This is a significant result considering that a strong connection of the melt length with the thickness of the ice cover has been observed. The length of melt has also increased by 5, and 7 days per decade over Greenland, and the permafrost areas of North America, respectively, but over permafrost areas in Eurasia, a negligible decrease is observed. Statistically derived projections are presented to illustrate how the perennial sea ice cover may look like in 2025, 2035, and 2060 when temperatures are predicted to reach the 2°C global increase. The open water area in the Central Arctic is projected to be increasing considerably with time likely causing profound changes in the ocean circulation, marine productivity, ecology and climate of the region.

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Abstract

The possible impact of an increase in global temperatures of about 2°C, as may be caused by a doubling of atmospheric CO_2, is studied using historical satellite records of surface temperatures and sea ice from late 1970s to 2003. Updated satellite data indicate that the perennial ice continued to decline at an even faster rate of 9.2 % per decade than previously reported while concurrently, the surface temperatures have steadily been going up in most places except for some parts of northern Russia. Surface temperature is shown to be highly correlated with sea ice concentration in the seasonal sea ice regions. Results of regression analysis indicates that for every 1°C increase in temperature, the perennial ice area decreases by about 1.48 x 10^6 km^2 with the correlation coefficient being significant but only -0.57. Arctic warming is estimated to be about 0.46°C per decade on average in the Arctic but is shown to be off center with respect to the North Pole, and is prominent mainly in the Western Arctic and North America. The length of melt has been increasing by 13 days per decade over sea ice covered areas suggesting a thinning in the ice cover. The length of melt also increased by 5 days per decade over Greenland, 7 days per decade over the permafrost areas of North America but practically no change in Eurasia. Statistically derived projections indicate that the perennial sea ice cover would decline considerably in 2025, 2035, and 2060 when temperatures are predicted by models to reach the 2°C global increase.

1. Introduction

The Arctic has been referred to as the "battleground" for climate change research because of possible amplification of a global change signal in the region (Budyko, 1966). A large fraction of the region is always covered by ice and snow, the reflectivity (or albedo) of which is high compared to that of open ocean and some other land surfaces. The ice and snow cover is also an effective insulator that limits the exchange of heat and energy between the surface and the atmosphere. Moreover, the ice and snow cover is especially sensitive to slight changes in surface temperature, especially when the surface is near melt temperatures. In this context, increases in surface temperature mean earlier onset of melt, delayed onset of freeze-up and therefore, thinning or earlier disappearance of the snow and ice cover. Amplification of a global change signal in the Arctic on account of the high albedo and insulating capacity of the surface has been confirmed in numerical models (Manabe et al., 1992) and has been estimated to range from 2 to 4 times (the global change) depending on model and model configuration (Holland and Bitz, 2003; New, this volume).

The last decade has been observed as the warmest since the beginning of the last century with the years 1998 and 2002 being the two warmest years. Such a trend in temperature has been associated with anthropogenic greenhouse warming (Hansen, 2004). The Arctic has indeed been showing signs that significant changes are occurring. The mountain glaciers have been retreating, permafrost has been thawing, snow cover has been diminishing, the Greenland ice sheet has been thinning and the Arctic sea ice cover has been declining (Comiso and Parkinson, 2004). Using the long term meteorological station data available from several stations (Jones et al., 1999), the average surface air temperatures at latitudes greater than 60 °N in the last 20 years have been shown to be increasing at a rate that is 8 times higher than that of the last 100 years (Comiso, 2003). This is in part caused by unusually warm temperatures during the 1930s. However, the latter is a more isolated warming confined to parts of the Northern Hemisphere while the warming in the last 25 years appears to be more global in scope (M. Serreze, personal communication, 2004). A study by Johannesen et al (2004) that made use of in situ surface temperature data concurrently with a numerical model also suggested that the warming episode earlier in the century was part of the natural climate variability while the more recent warming signal was a response to anthropogenic greenhouse forcing.

A doubling of CO_2 could mean an increase in global surface temperature of about 1 to 2 °C, according to a comparative study by Holland and Blitz (2003) and New (2004), who made use of results from several Global Circulation Models (GSM). A 2 °C increase would lead to an amplified increase of between 3 to 8 °C in the average surface temperature of the Arctic. In this paper, we make use of historical satellite temperature and sea ice data and updates of the analyses presented in Comiso (2002) and Comiso (2003) to study the possible effects of increases in temperatures of these magnitudes to the extent and area of the sea ice cover. The lack of good agreement of the results of the different models is an indication that at least some of the numerical models need to be enhanced before they can be used to accurately predict the future state of the Arctic sea ice cover. There are a few that matches observational data much better than others (Johannessen et al., 2004) suggesting progress in the right direction. Nevertheless, we can gain unique insights into the actual state of the Arctic from satellite observational data which provide first-hand information on how the system has been changing over the last 25 years on a continuous, day-to-day, month-to-month and year-to-year basis.

2. Satellite Infrared and Passive Microwave Observations

Satellite infrared and passive microwave sensors have provided continuous records of surface temperature and ice concentration, respectively, in the polar regions since the late 1970s (Parkinson et al., 1999; Comiso, 2003). Data from these type of sensors are especially useful for large scale seasonal, interannual, and spatial variability studies because of synoptic coverage at a relatively high temporal resolution. Infrared data are noted for day/night coverage during cloud free conditions at a moderate resolution (1-5 km) while passive microwave data provide day/night almost all weather coverage with a relatively coarse resolution (about 25 km). The effect of coarse resolution in the latter is minimized through the use of an ice algorithm that estimates the fraction of open water within the field-of-view of the satellite. Both data sets went through similar history of research development and have basically the same record lengths.

The monthly distributions of surface temperature and sea ice cover show the annual cycles associated with the change in seasons. There are other periodic patterns and phenomena, like the Northern Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) in the Arctic region (Venegas and Mysak, 2000; Thompson and Wallace, 1998) but the behavior of the associated indices are not too predictable and sometimes there are unexpected shifts in the phases of these cycles (Overland et al., 2002). Since our satellite record is only a little more than two decades in length, we will not do any harmonic decomposition of the data and will simply take into account the strong seasonal cycles when doing trend analysis.

2.1 Changes in Surface Temperature

Before the advent of satellite data, the only source of surface temperature data in the Arctic are those from relatively sparse meteorological stations over land and a few Argos buoys over the sea ice cover (Chapman and Walsh, 1993). The recent availability of historical data from a Russian ice station in the Central Arctic and other Russian land stations has enabled an improvement in statistics and led to the construction of interpolated data sets (e.g, IABP/POLES) on Arctic surface temperatures (Rigor et al., 2000, Johannessen et al., 2004) but the accuracy suffers in areas where there is little or no data. Satellite infrared data provide surface temperatures at good spatial and temporal resolution during clear sky conditions and has sufficient accuracy to provide meaningful representation of the horizontal distribution of temperatures in the entire Arctic (Steffen et al., 1993; Wang and Key, 2003; Comiso 2003). The longest record of satellite infrared data available is that provided by the Advanced Very High Resolution Radiometer (AVHRR). The lifetime of the sensor is about 5 to 10 years but the record is maintained by having the current one replaced by an almost identical new one every time the former shows any sign of degradation in performance. Despite efforts to get the sensors consistently calibrated on the ground, the characteristics of the sensor are normally altered slightly after launch making it necessary to refine the calibration and improve the temporal consistency of the record. This was done through the use of in situ data as discussed in Comiso (2003). For this study, the data record used by Comiso (2003) has been updated to include more recent data up to 2003. The entire data set is also further enhanced by improving on the consistency in the calibration through the use of a more comprehensive set of in situ data and by taking into account non-linearities in the calibration at high temperature values, especially in sub-polar regions.

Figures 1a and 1b show color-coded maps of the average of monthly surface temperatures over 5-year periods, the first from August 1981 to July 1986 and the second from August 1998 to July 2003. The two maps show striking similarities presenting basically the same general features with the cold regions being consistently in the same areas. The retreat of some of the cold isoterms from the 1980s to the 1990s is, however, apparent, especially in the Central Arctic (e.g., green colors), showing a movement towards warmer temperatures during the two periods. To assess the long term consistency of the AVHRR data set, a comparison of monthly temperature anomalies and trends between the IABP/POLES data set and the corresponding AVHRR data are presented in Figure 1c at three study regions (see rectangular boxes in Fig. 1b) where there are in situ data in the Arctic as described in Comiso (2003). Over the same time period, the variability in the anomalies is similar with the IABP/POLES data showing an overall trend of 0.42 ± 0.14 °C per decade while the AVHRR data show a comparable and consistent trend of 0.50 ± 0.16 °C per decade. Figure 1d shows a similar comparison of Jones et al (1999) data, including the Russian data, with AVHRR data (interpolated to the same location as the former) for the entire pan Arctic region (>60°N). The locations of the Jones data are indicated in Figure 1b as black cross marks. Again, the variabilities in the anomalies are consistent while the trends are in good agreement with the Jones data showing 0.35 ± 0.14 °C per decade while the AVHRR data shows 0.29 ± 0.15 °C per decade. While comparison of point measurements with AVHRR data show generally consistent patterns and trends, the trend from point measurements do not always reflect the trend over the entire region. For example, the AVHRR and Jones data sets provide comparable anomaly distributions and very similar trend values of 0.4 °C per decade in the sampled North American stations but the entire region (>60°N) yielded a trend of 0.8 °C per decade, which is twice higher. Excluding open ocean regions, the AVHRR record shows that the Arctic (>60°N) has been warming at the rate of 0.46 ± 0.11 °C per decade.

2.2 Changes in the Sea Ice Cover

The variability in the extent and area of the sea ice cover in the Northern Hemisphere has been discussed extensively in the literature (e.g., Chapman and Walsh, 1993; Bjorgo et al., 1997; Parkinson et al., 1999). These parameters are derived using ice concentration maps retrieved from satellite passive microwave data. By ice extent, we mean the total area of the ice covered portion of the ocean in which each data element has at least 15% sea ice concentration, while ice area is the total area in the ocean that is actually covered by sea ice. The seasonality of the ice cover is quite large with the ice extent ranging in value from a minimum of about 7 million km^2 at the end of the summer to a maximum of about 18 million km^2 during its peak in winter. The corresponding values in sea ice area are 6 million km^2 and 14 million km^2, respectively. Because of the large seasonality, monthly anomalies, derived by subtracting monthly climatologies from the values for each month, are used in interannual variability and trend studies.

One of the most remarkable changes in the Arctic is the rapidly retreating perennial ice cover as reported by Comiso (2002). Perennial ice is defined as the sea ice that survives the summer and its extent and area are determined from the ice cover data during the minimum extent at the end of the summer. It consists mainly of the thick multiyear ice floes which are the mainstay of the Arctic sea ice cover. One of the important implications of a retreating perennial ice is that as the fraction of multiyear ice floes decreases and the fraction of seasonal ice floes increases, the average thickness of the ice cover becomes thinner and more vulnerable to summer melt.

The study by Comiso (2002) showed that the extent and area of the perennial ice cover have declined at the rates of 6.5%/decade and 8.9 %/decade, respectively, from 1978 to 2000. Johanessen et al., (1999) also reported a decline of 7%/decade in the multiyear ice cover observed in winter. More recent data indicate that the trend is ongoing with the perennial ice cover reaching its lowest value during the satellite era in 2002. This is consistent with observations of summer ice by Serreze et al. (2003). Furthermore, the perennial ice cover in 2003 was also nearly as low as in 2002 (Comiso and Parkinson, 2004), suggesting that a recovery of the perennial ice cover is not in sight. To illustrate the magnitude of the change, Figures 2a and 2b show the Arctic perennial ice cover during it's highest and lowest extents in 1980, and 2002, respectively. The two images show contrasting ice cover with the difference in the perennial ice areas being about 1.6

million km^2, about 4 times the size of California. Updated versions of the extent and area of the perennial ice cover presented in the Comiso (2002) paper are shown in Figure 2c and with the inclusion of data up to 2003, the extent now declines at 7.1 ± 1.8 %/decade while the ice area declines at 9.2 ± 1.7 %/decade. The errors cited are just the statistical errors with the 95% confidence level being between -11.4% to -3.6% for extent while the 95% confidence level being between -12.5% and -5.7% for ice area. The persistence of abnormally low perennial ice area since 1998 is intriguing and opens up the question of how long such a trend would continue into the future. Currently available data for 2004 (i.e., as of September 12, 2004) already indicate that the extent and area of the perennial ice cover for 2004 is also a record low and at least lower than that of 2003.

For comparison, Figure 2d shows plots of monthly anomalies of ice extent and ice area in the entire Northern Hemisphere for the period November 1978 through June 2004. Both plots show considerable variability, reflecting interannual changes in growth and decay patterns. Linear regression analysis on the data reveals that the extent and area of the entire Northern Hemisphere ice cover have been declining but only at the rates of 2.4 ± 0.2 %/decade and 3.3 ± 0.2 %/decade, respectively. These trends are relatively low mainly because in winter, the ice cover has not been changing much and is even increasing in some areas like the Bering Sea. The interannual changes in the ice cover are actually most pronounced in the spring and the summer when changes in surface temperature are also relatively large.

3. Relationships of Surface Temperature with the Sea Ice Cover

It is intuitive to postulate that the observed decline in the sea ice cover is a natural consequence of the observed warming in the Arctic. The availability of coincident and co-registered satellite data of these variables makes it possible to establish the connection quantitatively. However, care in the interpretation of the data is necessary since the available data may be lacking in information content. In particular, we have detailed measurements of the ice extent and area but not of the thickness of the sea ice cover. Since increases in surface temperatures are more impacting to thin ice than to the thicker ice types on a short term basis, inability to assess the corresponding changes in thickness is a drawback. Furthermore, the influence of temperature on the area of sea ice also has a lag, the length of which depends on ice type and thickness of both ice and its snow cover. The temperature of the sea ice surface is also basically constant during the summer and is almost always near melt temperatures. Thus, interannual changes in the ice cover associated with changes in average surface temperature are sometimes not evident in the data until the ice melts out completely. In the other seasons when yearly variations are more likely, the surface can be so cold (except in late spring and early autumn) that even significant changes in temperature would have no effect on the ice area. Moreover, the growth and decay of the sea ice cover is also influenced by many other factors including wind strength and direction, ocean current, and tides. Interannual changes in sea level pressure have been observed (Walsh et al., 1996) and changes in the rates of occurrences in storms can alter the vertical distribution of the underlying warmer water (Yang et al., 2004) thereby impacting the sea ice cover. The number of storms and the tracks of these storms have changed in relation to the Arctic and North Atlantic Oscillations, and changes in the NAO may have changed the upper ocean as discussed by Maslowski et al. (2000, 2001). The impact of changing wind directions can also be considerable since wind can cause the advection of sea ice floes to warm water where they melt (Rigors et al., 2002). The observed changes in wind circulation from cyclonic to anti-cyclonic along the Alaska coastline was studied by Comiso et al., (2003) and shown to be correlated with large changes in the ice cover from 1996 to 1998.

The trends in surface temperature and sea ice concentration in the Arctic, as observed during the satellite era, are presented in Figure 3. Figure 3a is a spatially detailed representation of trends in surface temperature for the pan-Arctic region inferred from linear regression on the monthly anomalies from August 1981 to July 2003 on a pixel by pixel basis. The map shows a conspicuous lack of uniformity in the distribution of trends. Instead, there is an asymmetry in the distribution with the center of warming activity being concentrated in the Western Arctic, Northern Canada, and Greenland. More modest trends are apparent in surrounding areas and are even negative in parts of Eurasia. The trend patterns are also different for different seasons, with the average trend in the entire Arctic (>60 °N) being highest in spring at 0.81 ± 0.30 °C per decade, moderate but significant in summer and autumn at 0.41 ± 0.23 and 0.45 ± 0.28 °C per decade, respectively, and lowest and insignificant in winter at 0.27 ± 0.27 °C per decade. The errors quoted are just statistical errors and do not include possible systematic errors. The spatial distribution in the trends in spring are shown in Figure 3b with those in North America and Western Arctic being considerably more enhanced than those of the yearly trend.

To gain insights into the possible relationships of surface temperature with the sea ice cover, Figure 3c shows the trend maps in the yearly ice concentration over the same period while Figure 3d shows the corresponding trends in the perennial ice cover as observed during ice minima in September for each year. Qualitatively, the patterns are coherent in that areas showing positive trends in temperature are generally in areas showing large decreases in ice concentration. The large positive trends in surface temperatures are in part caused by more open water surfaces in later years due to the retreat of the perennial ice cover. In some areas as in the Eastern Bering Sea (60°N, 180°E), where there is a slight cooling, the ice cover is also increasing. The trends in the ice concentration of the perennial ice cover show more dramatic decline than those for the yearly averaged ice cover, especially in the Western Arctic. It is also apparent that the ice trend is most negative in areas where there is a significantly enhanced warming in spring. In Figure 3c, sea ice concentration is shown to be increasing along the Canadian side of the Arctic Ocean where surface temperature is shown to be increasing. This may be an example of the effect of winds packing ice against coastal areas.

The correlation of monthly sea ice concentration with monthly surface temperature on a pixel-by-pixel basis, is generally strong as illustrated by the correlation map between these two variables as presented in Figure 4a. The correlations are especially high in the seasonal sea ice regions (the correlation coefficients being mainly negative and greater than 0.7) where the ice is relatively thinner than other areas. As expected, the correlation is not so good in the perennial ice region and sometimes even positive where thick ice floes are pack together and do not get melted completely to cause a change in ice concentration as the surface temperature goes up to above freezing temperatures. In the open water areas in the summer, there is also a slight bias since the concentration does not change as the surface temperature goes up by a few degrees C.

The length of melt period is also considered as an important factor affecting the sea ice cover, especially that of the ice thickness (Hakkinen and Mellor, 1990; Laxon et al., 2003). Figure 4b shows the spatial distribution of the length of the melt period on average, using 1981-2003 AVHRR data. The length is minimal in Greenland, very low at the North Pole and vicinity, and increases progressively to the south. The trend map of the length of the melt period (not shown) indicate patterns similar to those of Figure 3a. To assess the trend in the length of the melt period, the areas with temperatures above freezing were calculated for each week and plotted as a function of time for each of the general regions: sea ice, Greenland, and in the discontinuous permafrost areas of Eurasia and North America (see red line). The width (i.e., 2σ) of the approximately Gaussian distribution of the areas for each year is estimated by fitting a Gaussian to each of the yearly distributions. Twice this width is used as a measure of the length of melt, as was done in Comiso (2003) and the results are presented in Figure 5. The length of melt is shown to be increasing at a relatively high rate of 13.1 days per decade for sea ice. This result is different from previous estimates for sea ice (e.g., Comiso, 2003) in that ocean areas that becomes ice free in spring and summer are included in the analysis. The relatively high value is likely an important reason for the current rapid decline of the perennial ice cover. The length of melt is also observed to be increasing at 4.1 days per decade over Greenland, and 5.4 days per decade over the discontinuous permafrost areas in North America. In Eurasia, however, a slight but insignificant decrease of -0.3 days per decade is observed over the discontinuous permafrost region. It appears that the permafrost regions in North America are more vulnerable to thawing than those in Eurasia.

4. Regression studies of temperature with the perennial ice cover

To minimize a possible bias associated with the near constant temperature of open water within the ice pack, surface ice temperatures are calculated only for surfaces with sea ice concentrations > 80% when we evaluate the averages over the sea ice cover. This threshold was used instead of a higher value to allow for a more comprehensive study area and better statistics. The results actually yielded similar correlation values when the threshold was increased to >90% or even higher. The resulting relationship is that for every 1 °C increase in yearly temperature, the perennial ice cover decreases by 1.48×10^6 km^2. Such a result is intriguing considering that the decrease corresponds to about 30% of the area of the perennial ice cover in 2002. It should be noted, however, that while the correlation between surface ice temperature and the perennial sea ice cover is significant, it is not very strong, the correlation coefficient being only -0.57. This result implies that only 32% of the variations in the perennial ice cover are accounted for by a linear relationship with surface temperature. Correlation analyses, using summer and spring temperatures only, did not yield better results, the correlation coefficients being -0.56 and

-0.51, respectively. The correlation with the winter temperature is significantly weaker with the correlation coefficient being -0.22. Similar correlation analyses were also done using different combinations and time lag analysis, but the results show even weaker correlations with the highest correlation coefficient being only around -0.3. As pointed out earlier, the lack of a stronger direct relationship between surface temperature and the perennial ice cover is associated with the complexity in the system as discussed in the following section.

5. Feedback Effects, Modeling Studies, and Projections

The ice-albedo feedback has been cited as one of the most important feedbacks in the Arctic, especially since 42% of the Greenhouse warming in the region has been attributed to this feedback by models. More specifically, as the perennial ice cover retreats, the effective albedo of the Arctic region decreases due to more open water and melt ponds, causing the absoption of more solar energy and thereby causing a warmer ocean and ice surface that in turn causes more melt and further retreat in the ice cover. Also, as the Arctic warms, the length of the melt period increases, hastening further thinning and decline in the ice cover. Furthermore, as the ice gets thinner, breakups becomes more frequent, throughout the year, causing the formation of more leads that causes the release of more heat to the atmosphere that in turn causes warmer air temperature. Such processes will continue until there is a drastic reversal in temperature and wind patterns. The restoration of the perennial ice cover would require sustained cooling, especially in the summer, to allow for more of the thinner seasonal ice cover to survive the summer and become multiyear ice. There are other feedbacks that are relevant, such as cloud feedbacks the sign of which changes depending on whether the clouds are low (which causes a cooling) or high (which causes a warming) as discussed by New (this volume). The ice-albedo feedback as applied in the Beaufort, Chukchi, and Siberia Seas, however, requires special attention, because of the abnormally large open water areas in the late summer in the region during the last 3 years (2002 to 2004).

Many advances in GCMs have occurred in recent years but it is apparent that more work needs to be done, as suggested by the lack of consistency in the predictions of different models (Holland and Bitz, 2003; New, this volume). The problem is that there are too many physical processes that need to be accounted for and different parameterization of these processes by the different models inevitably lead to different results. To cite a specific problem, the Arctic system is especially sensitive to the thickness of sea ice and hence the model whose sea ice cover is thin compared to those of others would have more sensitivity to greenhouse warming. Until the different models comes out with similar ice thickness distributions, which is currently not the case (Holland and Bitz, 2003; New, this Volume), they are not expected to provide identical results. It is encouraging, however, that all the models predict an amplified warming in the Arctic, and some results are comparable with those of observations (Johannessen et al., 2004).

The AVHRR data indicate that the Arctic region has been warming at the rate of about 0.46 °C per decade. Regression results also yielded that for every degree change in temperature, the perennial ice cover declines by 1.48×10^6 km^2. Knowing the amplification in the warming, it is straightforward to estimate the magnitude of the retreat in the perennial ice cover if the change is linear. But, the rate of warming has been changing, being lower at the beginning of the last century, and significantly higher in the last decade. In this study, we will use the results of New (this volume), which is based on more recent modeling study, that provide us with more specific dates when a doubling in CO_2 occurs. According to New (this volume), a 2°C global warming is projected by models to occur between the years 2026 to 2060.

To obtain an assessment of how the sea ice cover might be impacted during this time period, we make use of the statistics derived from 25-years of continuous and spatially detailed satellite data. A similar assessment was done in Comiso (2002) to get a forecast for the perennial ice cover in 2050. The technique we use for this current study is slightly different from the decadal projection used in the Comiso (2002) study. Our method is still relatively crude and simple and our assumption of a linear trend is likely not valid. However, the near term projections may produce a more realistic representation of nature than is currently predicted by models. For the longer term, adjustments in the dates may be necessary because of non-linear effects, and the possibility of a rebound.

The satellite ice concentrations maps during ice minima were used to assess the movement of the marginal ice zone at different longitudes, one degree apart. Along each longitude, the ice edge is identified and the trend for the northward advance of the ice edge is calculated using linear regression techniques. Five-year running averages were used to minimize the noise and a smoothing is done on the results to minimize large changes in the trend from one longitude to another. Except for the region north of Greenland and the adjacent part of the Canadian Archipelago where the ice edge is basically adjacent to land, the resulting trend values are used to make the projections.

The current five-year average for the perennial ice cover (i.e., from 1999 to 2003) is presented in Figure 6a. Starting with this 5-year average (representing 2001), a projection for the future of the perennial ice cover is done using results from the trend analysis on the ice edge/marginal ice zones. Figures 6b to 6d provide our projection of how the perennial ice cover might look like for the years 2025, 2035 and 2060. In the images, the changes are basically around the peripheral seas at the ice edge moving progressively to the north with time as dictated by the results of the regression analysis. Again, it is important to note that this projection is mainly statistical and assumes a linear trend which may not be a realistic assumption. The accuracy of this projection is difficult to assess but statistical analysis indicate that at a 95% confidence level, the trend in the decrease in the perennial ice area is between -5.7%/decade and -12.5%/decade. It is interesting to note, that the general characteristics of the perennial ice cover in 2002 to 2003 are consistent with the predictions of the Comiso (2002) study. Our current prediction is also showing good consistency with the perennial ice cover in 2004, the extent of which appears to be the second lowest during the satellite era. It should also be noted that the projected ice distributions provide patterns which are similar to those projected by some models (e.g., Johannessen et al., 2004)

6. Discussions and Conclusions

Global warming in the Arctic is to a certain degree already manifested by observed retreat of ice and snow, melt of glaciers, thawing of permafrost, and retreat of the sea ice cover. We are currently observing a rapidly retreating perennial sea ice cover during the twenty five year observational period when concurrently, the surface temperature went up by about 1°C. An update of data used in previous reports show that the perennial ice cover continued to decline at an even faster rate of 9.2 % per decade while the surface temperature has been steadily going up in most places except parts of northern Russia. It is also apparent that the most rapid retreat in the perennial ice cover has been occurring in the Beaufort Sea region while warming is going on in adjacent regions, including North America and Greenland. Some slight cooling is actually going on in parts of the Eastern Arctic, especially in Eastern Russia, but this may be generally due in part because the center of warming activity is shifted to the Western Arctic and North America and off-center with respect to the North Pole. This result is intriguing and may mean that the physics of the polar amplification due to feedback effects is more complex than previously assumed, especially in models.

The length of melt patterns, however, appears to be more symmetrical with the North Pole and progressively increase to the south except in Greenland and glacier areas. The length of melt, which has been shown to be sensitive to the thickness of the sea ice cover, is observed to be increasing at a rapid rate of 13.1 days per decade over sea ice covered regions. It is also increasing at the rate of 4.3 and 5.3 days per decade in Greenland and the permafrost regions of North America while the change is negligible over the permafrost regions of Eurasia.

Results of linear regression analysis suggest that for every 1°C increase in surface temperature, the area of the perennial ice cover decreases by about 1.48×10^6 km^2. The correlation of the two variables is significant but not very high with the correlation coefficient being only 0.57, but this is not totally unexpected. Temperature affects not only area but also volume and when the ice is very thick, for example, increases in temperature may not be reflected as decreases in ice area until the ice is thin enough to get melted completely. The correlation analysis on a pixel by pixel basis shows very high correlation between sea ice concentration and temperature in the seasonal ice region, where the ice cover is relatively thin and melts completely in summer, but not in the perennial ice area where the ice is thick and may not show corresponding changes in area. Moreover, the growth and decay of sea ice is affected by other factors such as wind, ocean current, cloud cover and tides. For example, changes in wind circulation could cause ice to be advected to warmer oceans during some years and not in other years. Also, an increase in the frequency of storms may alter the characteristics of the upper ocean and cause a change in the melt patterns for the sea ice.

Using statistical analysis, currently observed distribution of the perennial ice cover is projected into the years 2025, 2035, and 2060, when a 2°C global warming is expected to occur (New, this volume), and the results show ever increasing open ocean areas in the Beaufort, Siberian, Laptev and Kara Seas. The impact of such a largely increasing open water area could be profound. It could mean changes in the ocean circulation, marine productivity, ecology, ocean circulation and the climate of the region. It could also allow for much more extensive shipping and human activities in the region. A discussion of specific details of the impacts and mitigation strategies would require a separate study. The linear regression model used in the projection technique may not be a realistic model for the complex Arctic system but the results could provide useful insights into how the Arctic ice may change on a short term basis especially since previous projections successfully reproduced recent data. Again, we point out that the technique does not allow for the sea ice cover to rebound, which is a possibility, especially in response to AO and NAO. However, if the trend continues, the ice-albedo feedback effects may dominate and the projections would provide us with a good idea on how the perennial ice may be like when a doubling in the atmospheric CO_2 concentration occurs.

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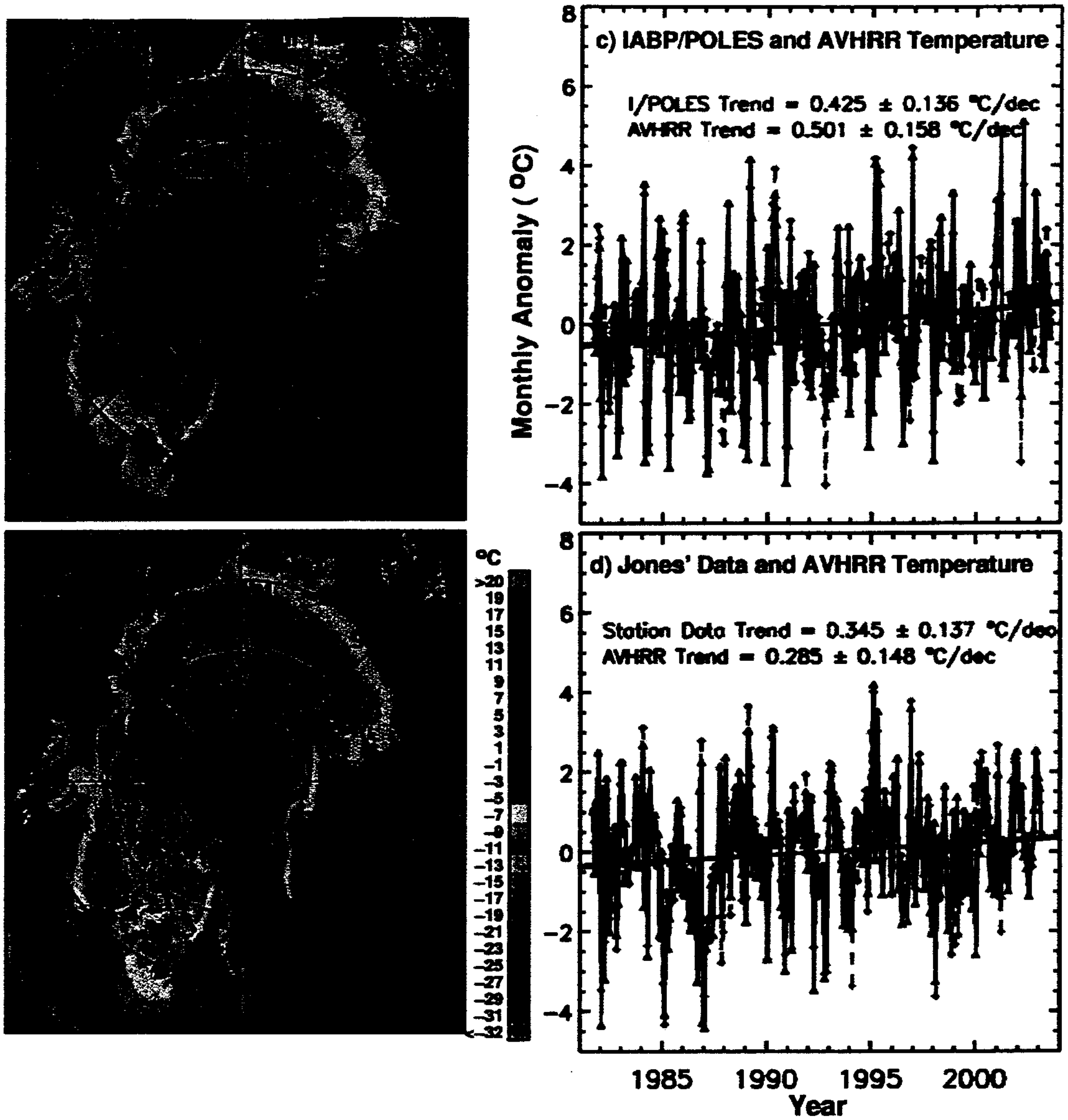

Figure 1. (a) Color-coded map of average surface temperatures from August 1981 to July 1986; (b) Color-coded map of average surface temperatures from August 1998 to July 2003; Anomalies and trend results using (c) IABP/POLES data averaged over three locations and the corresponding AVHRR data averaged over the same locations; and (d) combined Jones et al. and Russian and corresponding AVHRR data

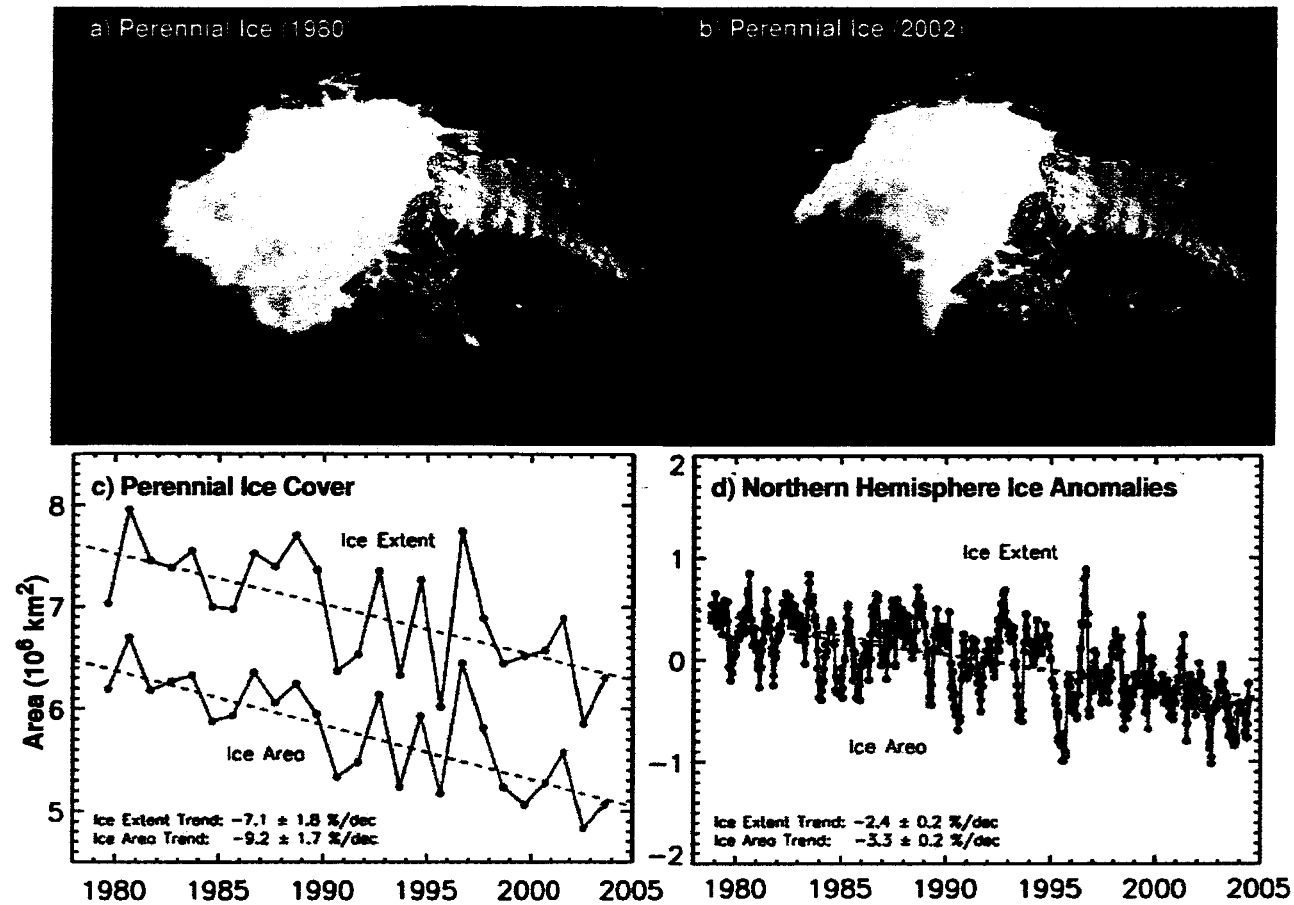

Figure 2. Ice concentration map (in arbitrary scale with white being 100% ice) of the perennial ice cover in (a) 1980 and (b) 2002 with MODIS land cover data used over land surfaces. (c) Arctic perennial ice extent and areas with trend lines and (d) monthly anomalies in the extent (blue) and area (green) with trend lines for the entire Northern Hemisphere.

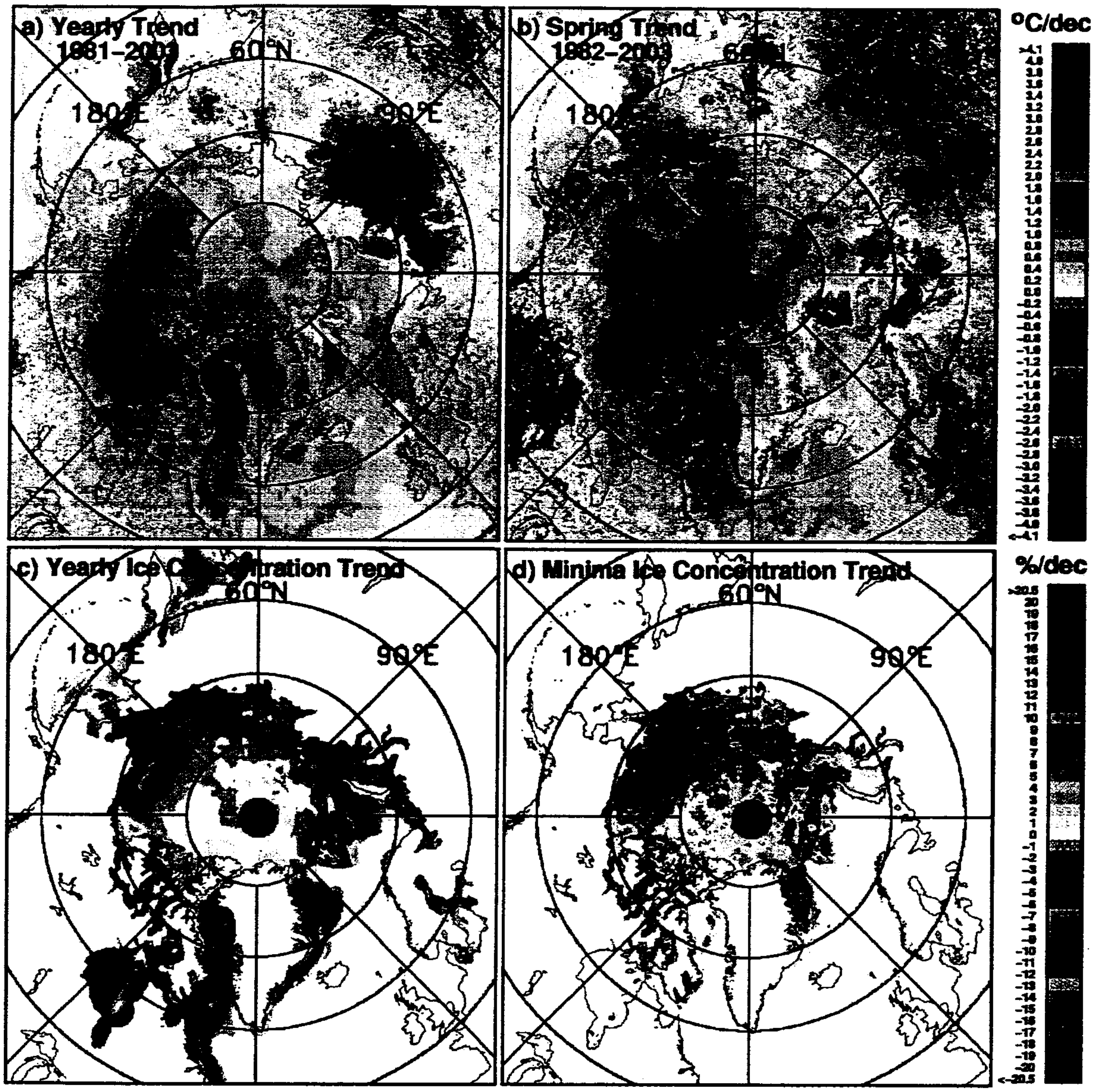

Figure 3. Color coded maps of (a) trends in surface temperature using monthly anomaly data (1981-2003); (b) trends in surface temperature during spring (1981-2003); (c) trends in sea ice concentrations using monthly anomaly data (1979-2003); and (d) trends in the perennial ice cover (1979-2003).

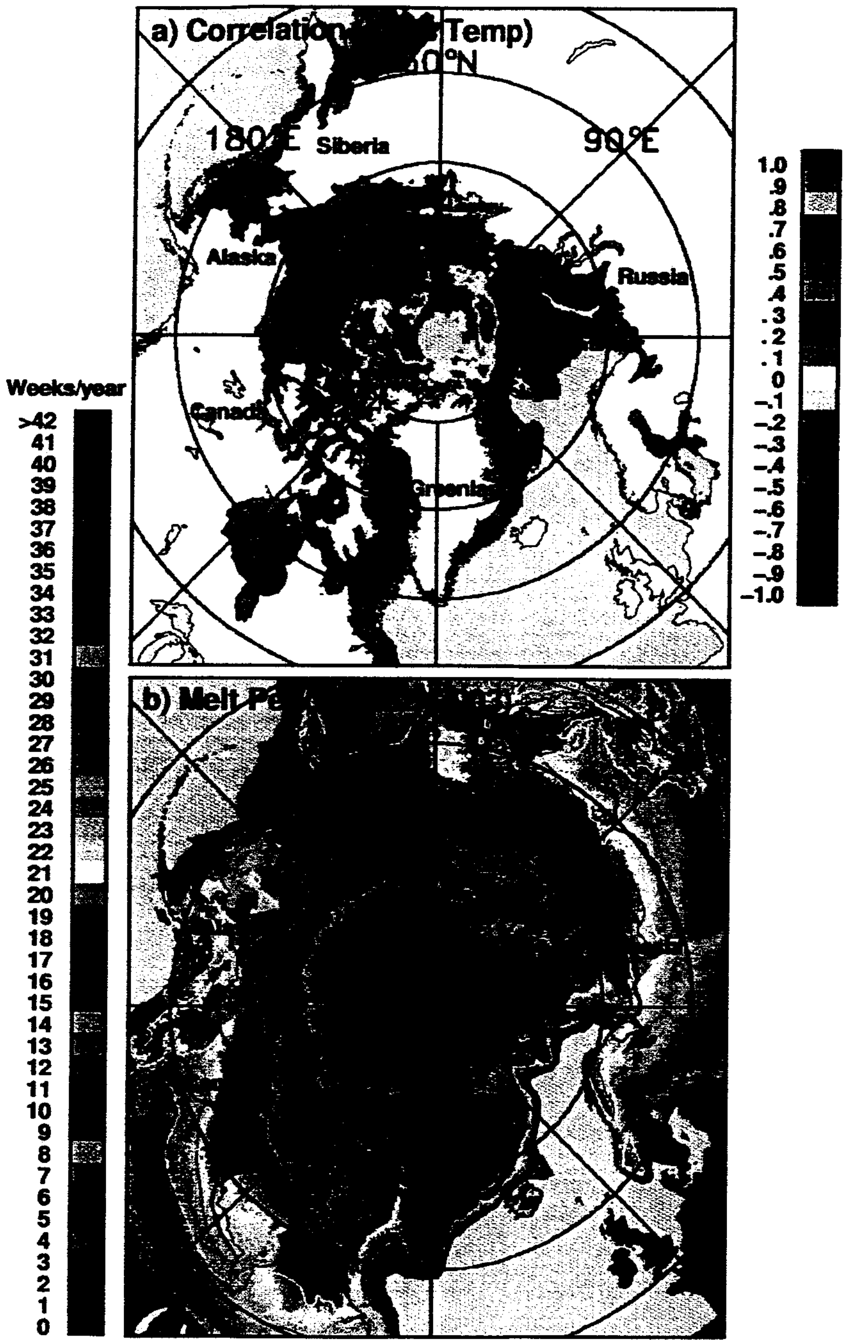

Figure 4. Color-coded maps of (a) correlation coefficients from regression analyses between ice concentration and surface temperature using yearly data from 1981 to 2003; and (b) climatological average (1982-2003) of the length of melt derived for each year by using weekly temperature data. The contour lines represent boundaries of sporadic (blue), discontinuous (green) and continuous (red) permafrost as inferred from UNEP data.

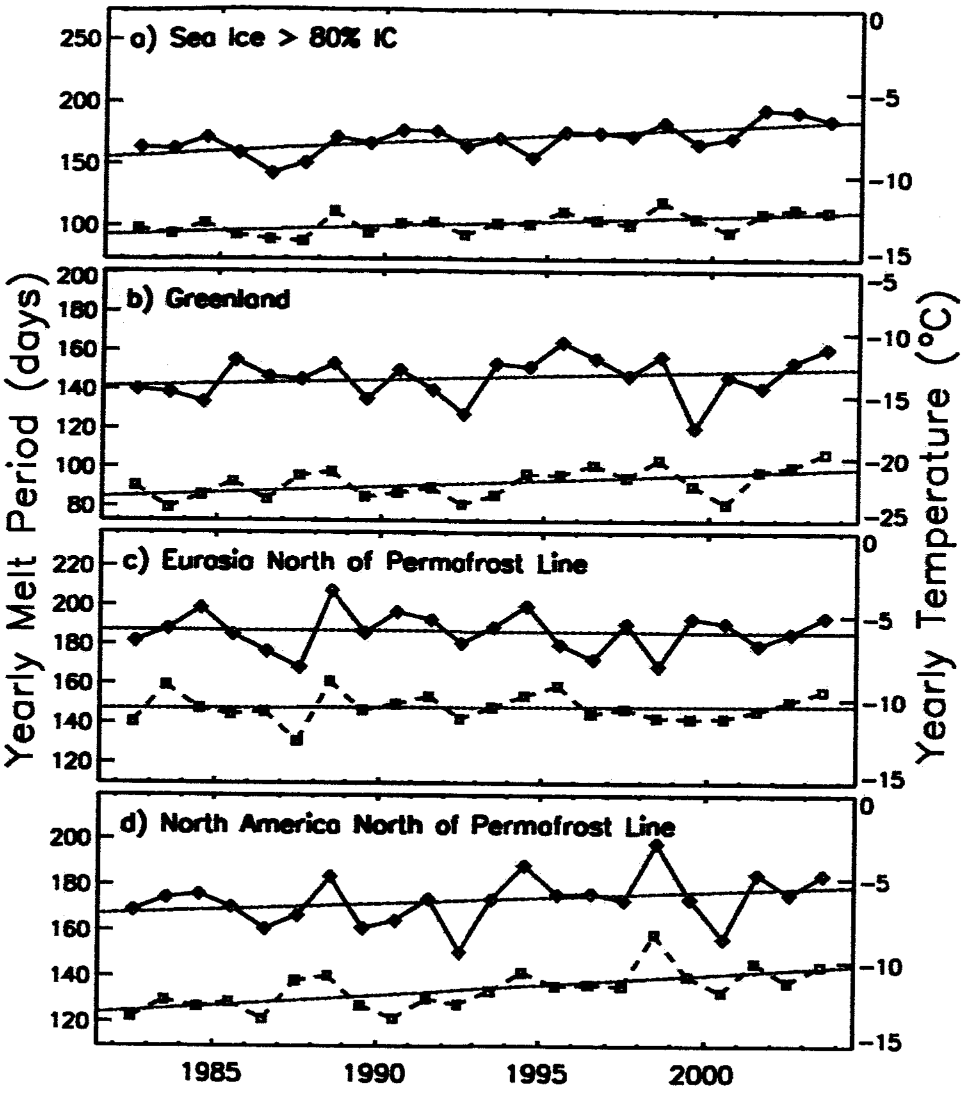

Figure 5. Yearly lengths of melt (in blue) over (a) sea ice (IC>80%); (b) Greenland; (c) north of discontinuous permafrost in Eurasia; and (d) north of discontinuous permafrost in North America. The plots in red are yearly averages (January to December) of surface temperature for each year.

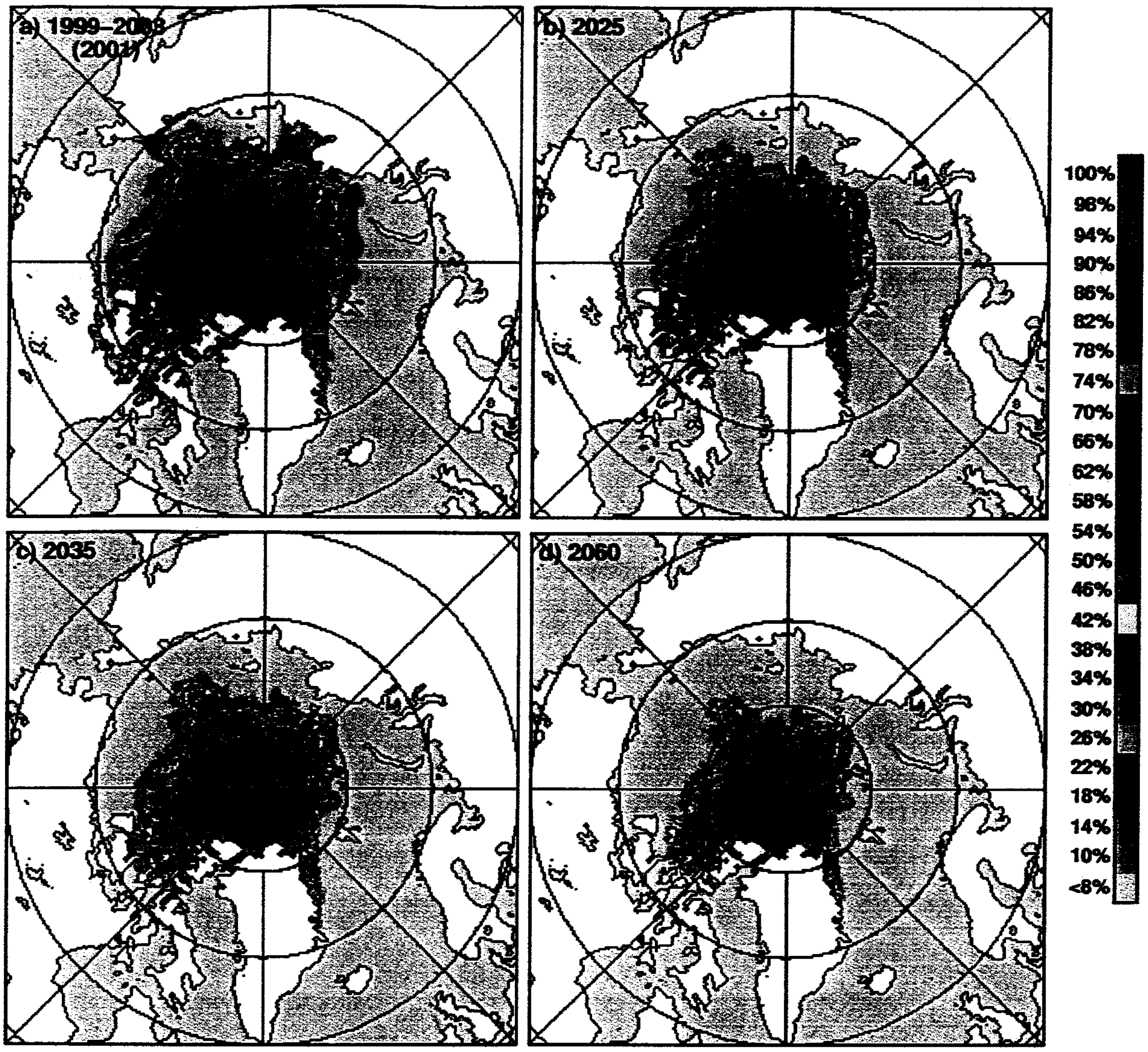

Figure 6. (a) Color coded map of the average of the Arctic perennial ice cover from 1998 to 2003. Projections of a five-year running average of the perennial ice concentration data from 1978 to 2003 for the years (b) 2025; (c) 2035; and (d) 2060. A small circular area around the North Pole with no data because of satellite orbit inclination has been filled up using spatial interpolation.