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Correlation and trend studies of the sea-ice cover and surface temperatures in the Arctic

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ABSTRACT. Co-registered and continuous satellite data of sea-ice concentrations and surface ice temperatures from 1981 to 2000 are analyzed to evaluate relationships between these two critical climate parameters and what they reveal in tandem about the changing Arctic environment. During the 19 year period, the Arctic ice extent and actual ice area are shown to be declining at a rate of $-2.0 \pm 0.3\%\ \mathrm{dec}^{-1}$ and $3.1 \pm 0.4\%\ \mathrm{dec}^{-1}$, respectively, while the surface ice temperature has been increasing at $0.4 \pm 0.2\ \mathrm{K\ dec}^{-1}$, where dec is decade. The extent and area of the perennial ice cover, estimated from summer minimum values, have been declining at a much faster rate of $-6.7 \pm 2.4\%\ \mathrm{dec}^{-1}$ and $-8.3 \pm 2.4\%\ \mathrm{dec}^{-1}$, respectively, while the surface ice temperature has been increasing at $0.9 \pm 0.6\ \mathrm{K\ dec}^{-1}$. This unusual rate of decline is accompanied by a very variable summer ice cover in the 1990s compared to the 1980s, suggesting increases in the fraction of the relatively thin second-year, and hence a thinning in the perennial, ice cover during the last two decades. Yearly anomaly maps show that the ice-concentration anomalies are predominantly positive in the 1980s and negative in the 1990s, while surface temperature anomalies were mainly negative in the 1980s and positive in the 1990s. The yearly ice-concentration and surface temperature anomalies are highly correlated, indicating a strong link especially in the seasonal region and around the periphery of the perennial ice cover. The surface temperature anomalies also reveal the spatial scope of each warming (or cooling) phenomenon that usually extends beyond the boundaries of the sea-ice cover.

INTRODUCTION

The Arctic region is of particular interest because it is expected to provide early signals associated with a potential change in climate (Budyko, 1966; Manabe and others, 1992; Alley, 1995). Because of observed global warming, especially in the second half of the 1990s (Jones and others, 1999), it is important to know how such increases in temperature are reflected in the Arctic. Recent reports show that the sea-ice cover has been retreating by about $-3\%\ \mathrm{dec}^{-1}$ (Bjørgo and others, 1997; Parkinson and others, 1999), while submarine sonar data show a thinning by >1 m in deep-water portions of the Arctic (Rothrock and others, 1999; Wadhams and Davis, 2000) over a period of 4 dec, where dec is decade. The Arctic climate system is, however, a very complex system affected by periodic atmospheric phenomena, like the North Atlantic and Arctic Oscillations (Mysak, 1999), and unexpected changes in ice-cover dynamics. Accurate interpretation of observed Arctic changes thus requires a better understanding of Arctic processes.

The key objective of this study is to make simultaneous use of satellite sea-ice concentration and surface temperature data to gain insight into the changing Arctic climate. Co-registered datasets of these two geophysical variables are examined to obtain a better understanding of how the various components of the climate system interact and how they act in concert to influence the system. Previous studies on the variability and trends of the Arctic sea-ice cover have been carried out using solely satellite passive-microwave data or submarine sonar data. In this study, trends and spatial changes in the ice cover are analyzed in conjunction with trends and changes in surface temperatures. Anomalies in ice concentration and surface temperatures are examined on a year-to-year basis, and relationships between these two variables are evaluated. The results are also used to gain insight into the observed changes in the Arctic, interpret trends in the total ice cover and its surface temperature, and better understand the status of the perennial sea-ice cover.

VARIABILITY AND TREND OF THE SEA-ICE COVER

Although a slightly longer time series for sea-ice cover is available, the time period used in this study is 1981–99 since this is the period for which coincident and continuous infrared and passive-microwave satellite data are available. The procedure for deriving ice concentration from satellite passive-microwave data has been described before (Comiso and others, 1997) and will not be repeated here. The error associated with the ice-concentration data is about 5–15% under dry surface conditions, and increases when the surface becomes wet as the snow melts in spring and when melt ponds are formed over ice floes in the summer. In this study, the ice concentrations are derived using the Bootstrap algorithm as described in Comiso and others (1997). The values and trends may therefore be slightly different from those reported elsewhere (Bjørgo and others 1997; Parkinson and others, 1999) even for identical periods.

Ice-concentration maps are used to derive monthly ice extent, actual ice area and average ice concentrations within the pack, as done previously (Comiso and others, 1997; Parkinson and others, 1999). These are in turn used to calculate anomalies in monthly ice extent, actual ice area and ice concentration by subtracting the 19 year climatological averages created for each of the 12 months of the year. The anomalies in ice extent, ice area and ice concentration for each month from August 1981 through July 2000, which are also used for trend studies, are shown in Figure 1. Yearly averages were also calculated for analysis of the yearly variability and associated trend. The yearly averaging was done from August of one year to July the following year to be able to compare yearly differences between different ice seasons, instead of different annual averages that would extend from the middle of one ice season to the middle of another.

The plot of ice-extent anomalies (Fig. 1a) shows significant variability, with a standard deviation of 0.33×10^6 km^2. Simple linear regression of the data yielded a trend of $-246\,000 \pm 40\,000$ km^2 dec^{-1}, or -2.04 ± 0.33% dec^{-1}. This is significantly less than the -2.8% dec^{-1} reported by Parkinson and others (1999), but the latter was for a slightly different time period (i.e. 1978–96) and a different ice dataset was used (i.e. Team algorithm as described in Comiso and others, 1997), as indicated earlier. Anomalously low values occurred in 1989, 1990, 1993, 1995 and 1998, while an anomalously high value is apparent in 1996. The regression results from the yearly data yielded -2.04 ± 0.56% dec^{-1} the result of which is almost the same as the monthly anomaly data but with higher error.

The variability in the anomalies in actual ice area (Fig. 1b) is comparable to that of ice extent, with a standard deviation of 0.33×10^6 km^2. However, the trend in ice area is significantly larger at $-336\,000 \pm 36\,000$ km^2 dec^{-1}, or -3.11 ± 0.33% dec^{-1}. This is more in line with previous reports for the 1978–96 period. The yearly averages yielded similar trends but larger error at -3.12 ± 0.51% dec^{-1}.

The difference between the ice-extent and ice-area trends stems mainly from a net negative trend in ice concentration (Fig. 1c), estimated at -1.16 ± 0.12% dec^{-1}. The change in estimated ice concentration may not be entirely due to a change in true ice concentration since it could also be linked to a change in the areal coverage of melt ponding. To test this possibility, a similar analysis was conducted that excluded the summer months (June–August). The results yielded a trend in ice concentration of -1.09 ± 0.14% dec^{-1}, which is similar to that with the summer months included. This implies that the impact of changes in melt-ponded area on the trend results is not significant. However, excluding the summer

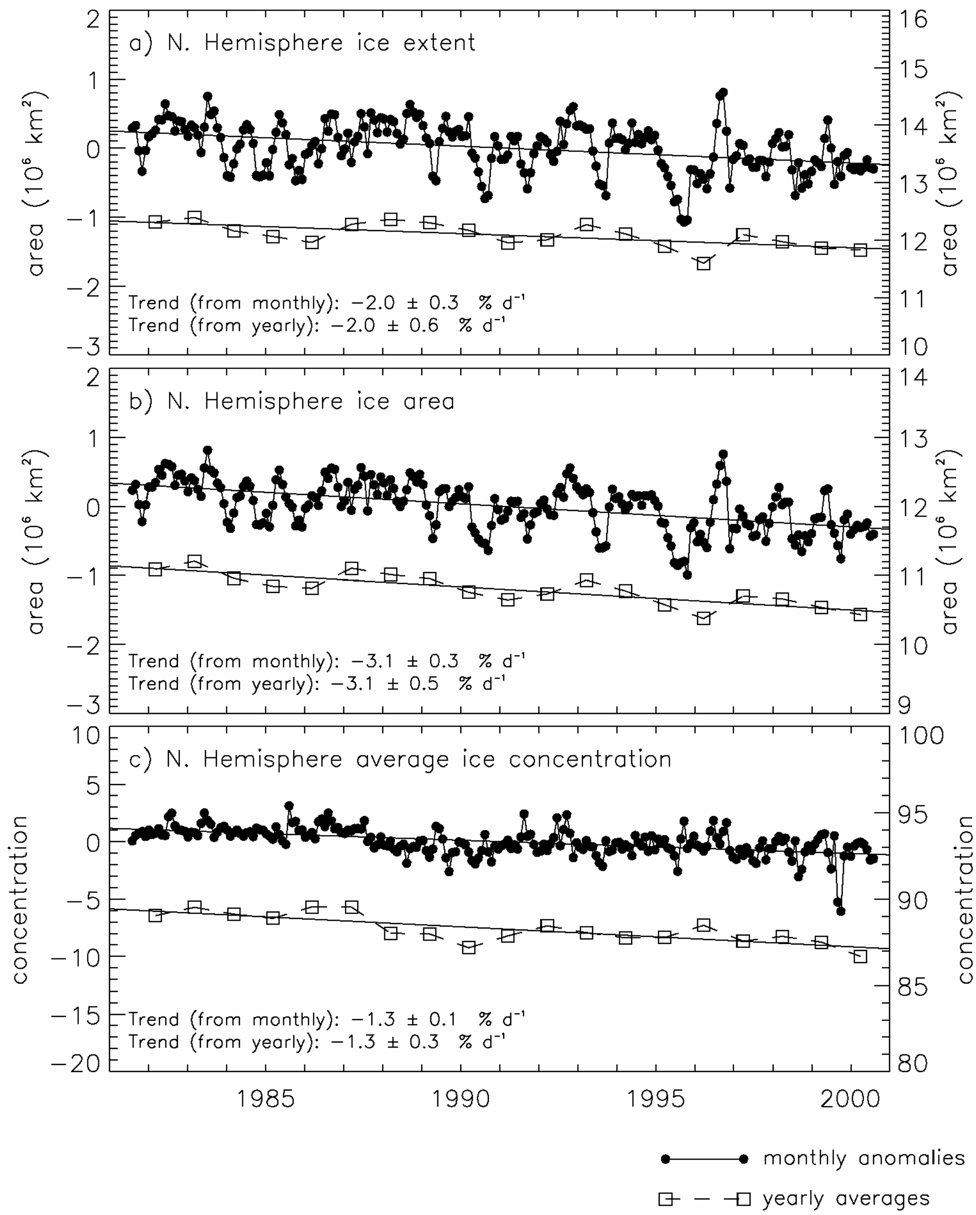

Fig. 1. Monthly anomalies and yearly averages of (a) sea-ice extent, (b) actual ice area and (c) ice concentration, 1981–2000, and associated trends from linear regression analysis. Yearly averages are from August to July the following year.

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months significantly reduced the trends in ice extent and area to $-1.47 \pm 0.14\%\ \mathrm{dec}^{-1}$ and $-2.47 \pm 0.37\%\ \mathrm{dec}^{-1}$, respectively. This suggests that the trends in the ice cover during the summer, especially during minima, may be high as indicated later.

The distributions for the yearly average extent and area in Figure 1 exhibit a periodic cycle with a period of about 5 years. Such periodicity is intriguing in light of a possible correlation with many important processes, such as the Arctic Oscillation. The effect is not so apparent in the monthly anomalies. However, a detailed study of this phenomenon is beyond the scope of this paper.

VARIABILITY AND TREND OF SURFACE TEMPERATURES

The procedure for deriving the surface temperature from satellite infrared data has been discussed elsewhere (Steffen and others, 1993; Comiso, 2000). The error in the retrieved monthly data has been estimated to be <3 K, as inferred from comparative analysis with in situ measurements. The precision of the geophysical products is likely better than the stated accuracy since the radiometer has an rms error of <1 K. Available in situ measurements are also only point measurements and may not exactly match the satellite data which have been gridded at 6.25 by 6.25 km^2. An improved validation can be obtained using high-resolution aircraft infrared measurements covering a region comparable in size to the satellite footprint and include in situ point measurements. Unfortunately, such measurements are not currently available in the polar regions.

The monthly average anomalies in surface temperatures over sea ice, Greenland and high-latitude land areas from August 1981 through July 1999 are presented in Figure 2a–c, respectively. The temperature anomalies over sea ice show significant interannual variations, with a standard deviation of about 1.3 K. A linear regression on the monthly anomalies resulted in a trend of $0.52 \pm 0.16\ \mathrm{K\ dec}^{-1}$, while yearly averages for the same dataset provided a trend of $0.52 \pm 0.19\ \mathrm{K\ dec}^{-1}$. The trend results from the monthly anomalies and yearly averages are consistent, but the errors in the yearly averages are slightly larger.

The monthly anomalies in temperature over Greenland (Fig. 2b) have greater variability than those over sea ice. The standard deviation of this variability is greater at 2.1 K, while the month-to-month change can be as large as 4 K. The

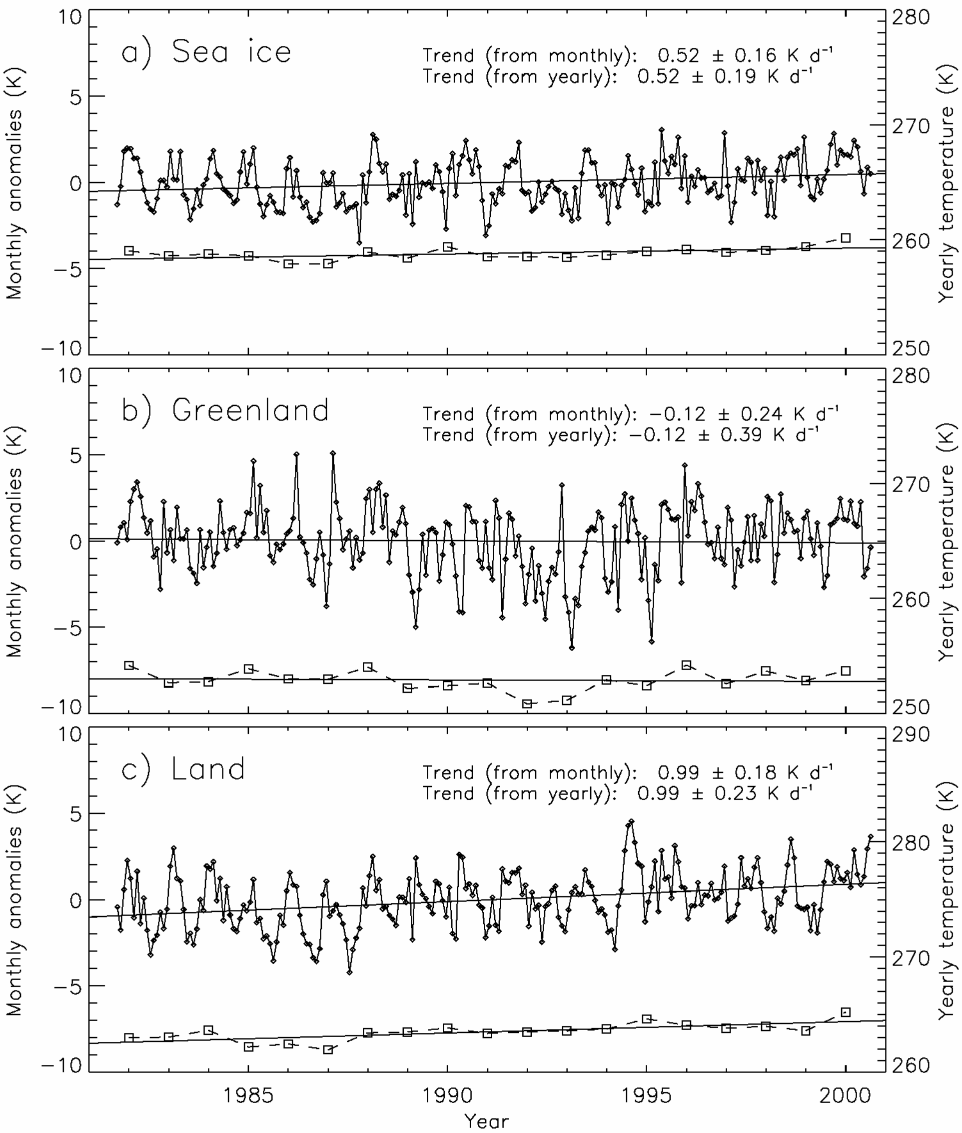

Fig. 2. Monthly anomalies and yearly averages of surface temperatures for 1981–2000 as well as trend analysis results over (a) sea ice, (b) Greenland and (c) land areas >60° N.

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regression results show a negative trend of $-0.12 \pm 0.24\,\mathrm{K\,dec^{-1}}$ for the monthly anomaly data and $-0.12 \pm 0.48\,\mathrm{K\,dec^{-1}}$ for the yearly data. Although the trend is negative and different from those of the other study areas, the magnitude of the trend is small compared to the error and is not considered significant.

For land areas other than Greenland and $>60^\circ$N, the anomalies are more variable than over sea ice but not as variable as for Greenland. The trend in this data is the highest among the three regions, at $0.99 \pm 0.18\,\mathrm{K\,dec^{-1}}$ for the monthly anomalies and $0.99 \pm 0.23\,\mathrm{K\,dec^{-1}}$ for the yearly data. The higher trend over land (except for Greenland) than over sea ice indicates that land areas are even more vulnerable to warming effects.

The warming trends derived from satellite data for sea ice and land are quite high compared to global averages derived from meteorological stations (Jones and others, 1999). The satellite dataset, however, is consistent with station data in station locations, and on a year-to-year basis. Also, there are areas, such as Greenland, that show cooling instead of warming. Although the record length is relatively short, and the accuracy of the data needs to be improved, the satellite data comprise the only dataset that can currently provide good spatial coverage.

CORRELATION OF ICE CONCENTRATION AND SURFACE TEMPERATURE

To show how the ice cover has been changing on a regional basis during the 1981–99 period, yearly anomalies in ice concentrations are depicted in Figure 3. The anomaly maps reveal the spots where the Arctic ice cover is increasing (grays, greens and blues) and where it is decreasing (oranges, purples and reds). Highly anomalous regions for each year are thus easily identifiable. For reference, the 19 year average of ice concentrations (1981–2000 climatology) used to generate the anomaly maps is shown in the last image in Figure 3. Generally, there is a predominance of anomalously high concentrations in the 1980s and anomalously low concentrations in the 1990s. It is thus not surprising that the trend analysis yielded negative results.

For comparative analysis, anomalies in surface temperatures are shown in Figure 4. In this case, increases are depicted in warm colors (yellows, oranges, reds and purples), while decreases are depicted in cool colors (greens, blues and grays). The anomalously warm areas represented by warm colors can readily be compared with anomalously low ice concentrations (similar colors) in Figure 3, and vice versa. The 19 year average surface temperature (climatology) is shown in the last image of Figure 4.

Anomalously cold areas predominate in the 1980s, and anomalously warm areas in the 1990s. This is consistent with Arctic warming as indicated previously, and with the anomalies in ice concentrations, but even in the 1980s there were distinctly warm anomalies such as in Greenland in 1981/82, Siberia in 1983/84 and northern Canada in 1987/88. Also, there were anomalously cold regions in the 1990s such as northern Canada in 1991/92, Greenland in 1992/93 and Russia in 1998/99.

A comparison of the anomalies in the Arctic sea-ice region (Fig. 3 vs Fig. 4) shows a strong coherence of ice concentration with surface temperature. The regions where ice anomalies were strongly positive are also regions where temperature anomalies were strongly negative and vice versa. We can learn much more from the temperature data than from the ice-concentration data because the study area is not confined to the sea-ice regions. As indicated by the images, the temperature-anomaly maps provide a more complete characterization of the scope of warming or cooling events in the Arctic. For instance, they show that a warming scenario extends considerably beyond the sea-ice regions. A good example is the retreat of the sea-ice cover in the Beaufort Sea during the 1997/98 and 1998/99 periods. This retreat is substantial, but the warming anomaly event in the region has a much wider scope and was even greater south of the Beaufort Sea. The temperature maps also show a cooling in northern Russia during the same period.

The temperature-anomaly maps also show some warming trends starting with the 1987/88 ice season. The trend was interrupted by a slight cooling from 1991 through 1994, which may have been the result of the Mount Pinatubo (Philippines) volcanic eruption in 1991. Also, while 1998 is considered the warmest year in the 20th century, cooling is apparent in northern Russia from 1997 through 1999.

The high coherence of the spatial features in the anomaly maps for the ice concentration, compared to those of surface temperatures, is intriguing. This was quantified by doing a regression analysis of the two variables on a pixel-by-pixel basis, using the 19 pairs of yearly anomaly maps. The results are shown in Figure 5 and expressed in terms of correlation coefficients for each sea-ice data point in the Arctic region. It is apparent from the color-coded map that the region of highest negative correlation (pinks and purples) is the seasonal sea-ice region. The correlation coefficients are also very high around the periphery of the perennial ice region. In the central Arctic, the correlation is poor, as would be expected since the ice concentration in the region is consistently high and changes very little, although the surface temperature may change substantially. Overall, the results show that the area most affected by warming is the seasonal region and the periphery of the perennial ice region.

VARIABILITY OF THE PERENNIAL ICE COVER

A study of the variability of the Arctic sea-ice cover is not complete without the study of the variability of its perennial ice cover. We define perennial ice cover as that which survives the summer melt period and is composed mainly of thick multi-year ice floes. The perennial ice cover is an important climate parameter since it strongly influences the thickness distribution of the ice cover. Negative changes in multi-year ice cover have been reported (Johannessen and others, 1999), but the data used for multi-year ice were inferred from the winter passive-microwave data which were previously reported to have large errors when compared with high-resolution synthetic aperture radar data (Kwok and others, 1996).

The best way to quantify the state of the perennial ice cover is to monitor how the minimum ice extent and ice area have been changing from year to year (Comiso, 1990). The minimum extent for the entire Arctic is hard to estimate since the ice minimum may occur at different times in different areas. One solution might be to examine the time history of each pixel and find the yearly minimum in each pixel. However, such a technique would be effective only if the ice pack were stationary and melt ponding did not occur. Because the ice pack is constantly moving, such

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a procedure will tend to choose ice pixels that may be temporarily displaced by open water because of wind. Also, melt ponds have a signature similar to that of open water and the procedure would choose predominantly melt-ponded pixels that yield lower concentrations than the true ice concentration. The results of such an analysis would be hard to interpret, if not erroneous.

A good approximation to the extent of the perennial ice cover is the minimum ice extent during the summer/autumn period. Changes in pressure fields that tend to move the perennial ice cover around the Arctic region are not a problem since the entire region is considered. It is also encouraging that the day of minimum ice extent (or area) has been found to occur at approximately the same time each year (i.e. early September). Thus, the year-to-year difference in the small percentage contamination of the data by first-year ice that formed during the summer is likely negligible. A 7 day running average of the daily extent or

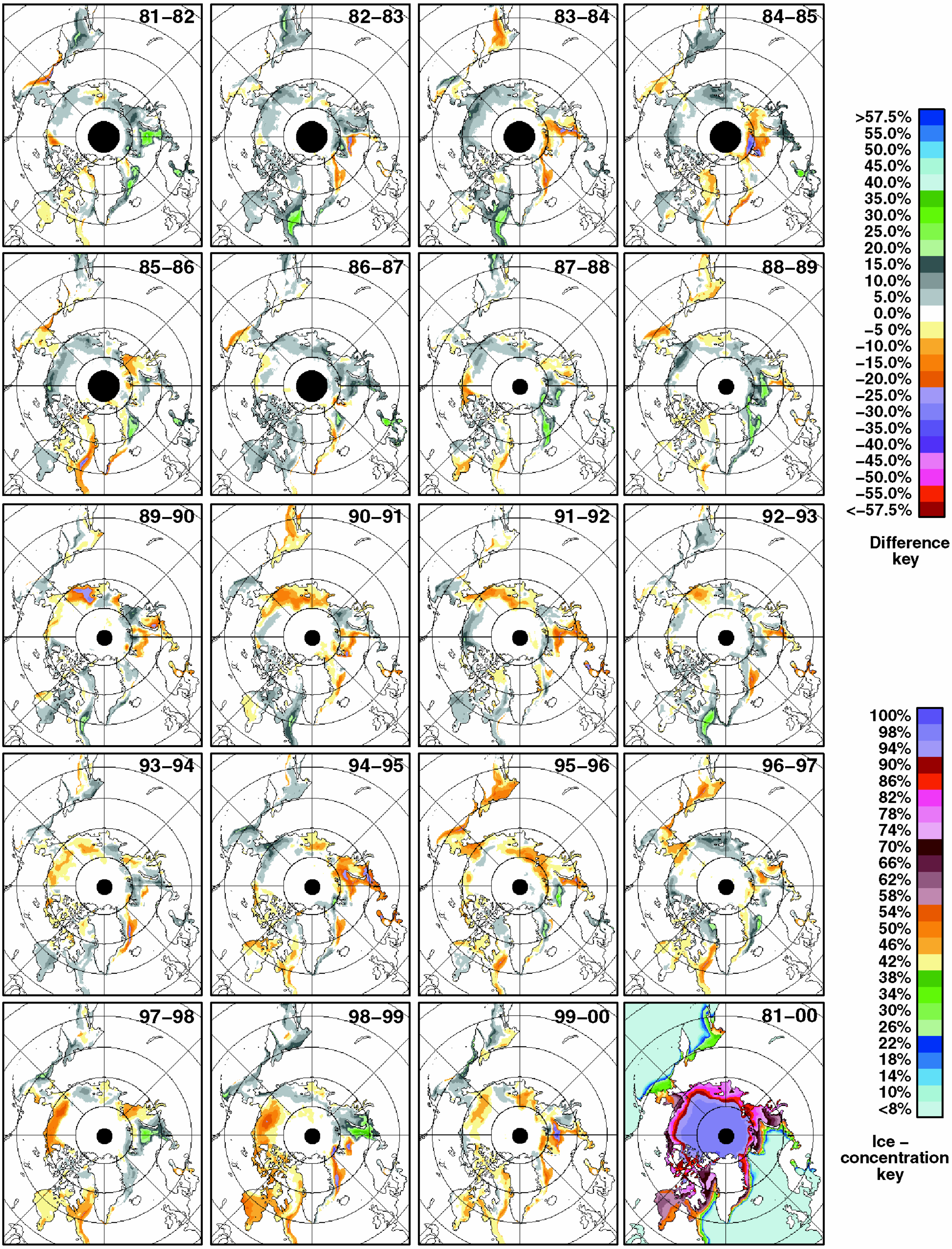

Fig. 3. Color-coded anomalies in ice concentration for each year 1981–2000. Yearly averages are from August to July the following year.

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area is also used to make it more likely that the date chosen for each year is for the real minimum.

The ice extent and actual ice during summer minima from 1981 through 2000 are shown in Figure 6. The plots show large yearly fluctuations in extent and area during the ice minimum in the 1990s, while there are no such fluctuations in the 1980s. The period of yearly fluctuation is 1991–97. The average fluctuation is about 10^6 km^2, but from 1995 to 1996 the ice extent increased by almost 2×10^6 km^2. A large increase from one year to another usually means a large increase in the area covered by second-year ice cover since older ice types cannot increase area from one year to the next. Conversely, large decreases mean the decrease of all types of perennial ice cover that includes second-year ice and the thicker, older ice types. An alternate yearly fluctuation of increases and decreases in areal coverage would thus mean the introduction of younger, thinner ice types. Repetition of this process would imply an overall thinning in the ice cover.

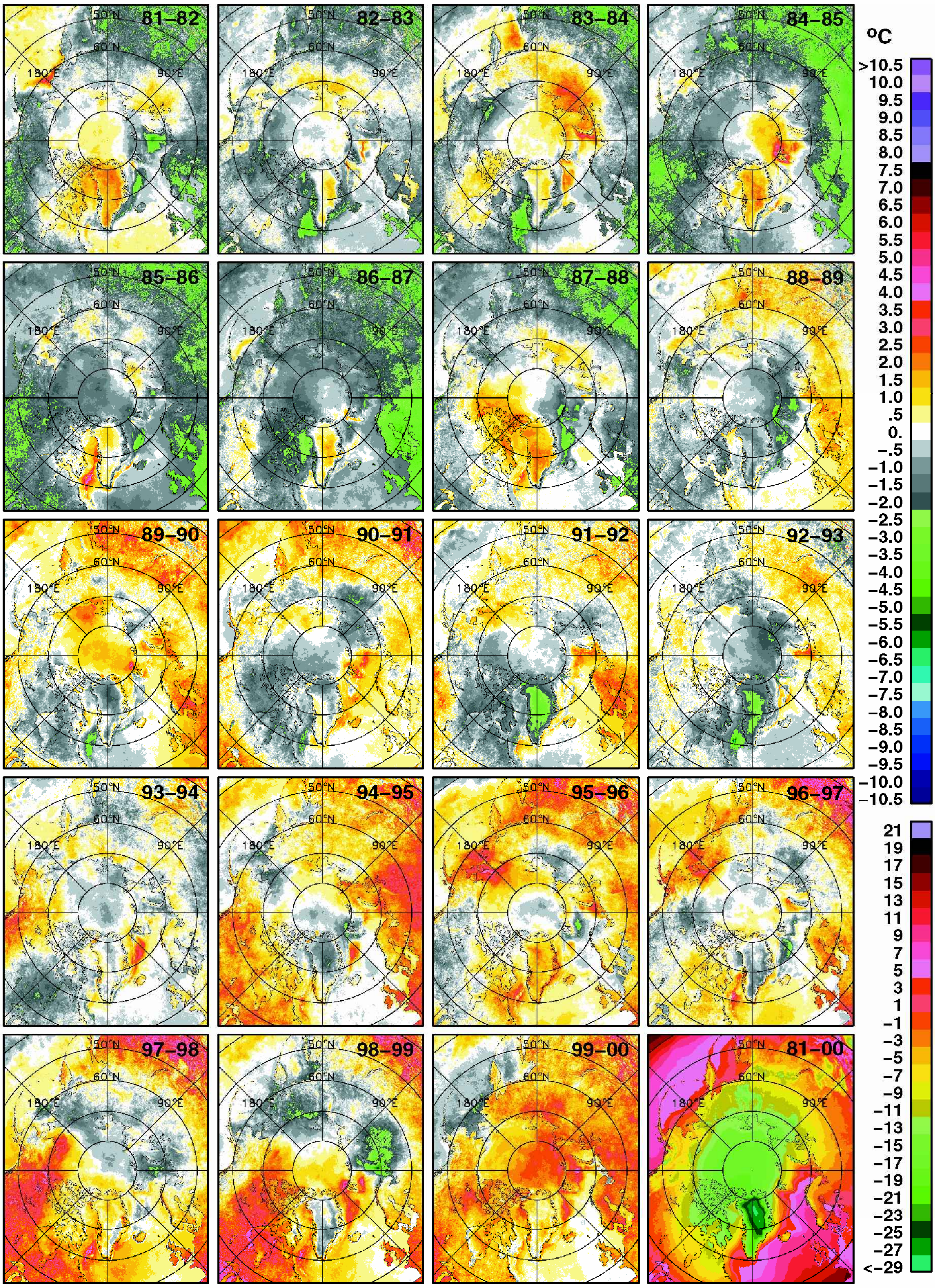

Fig. 4. Color-coded anomalies in surface temperature for each year 1981–2000. Yearly averages are from August to July the following year.

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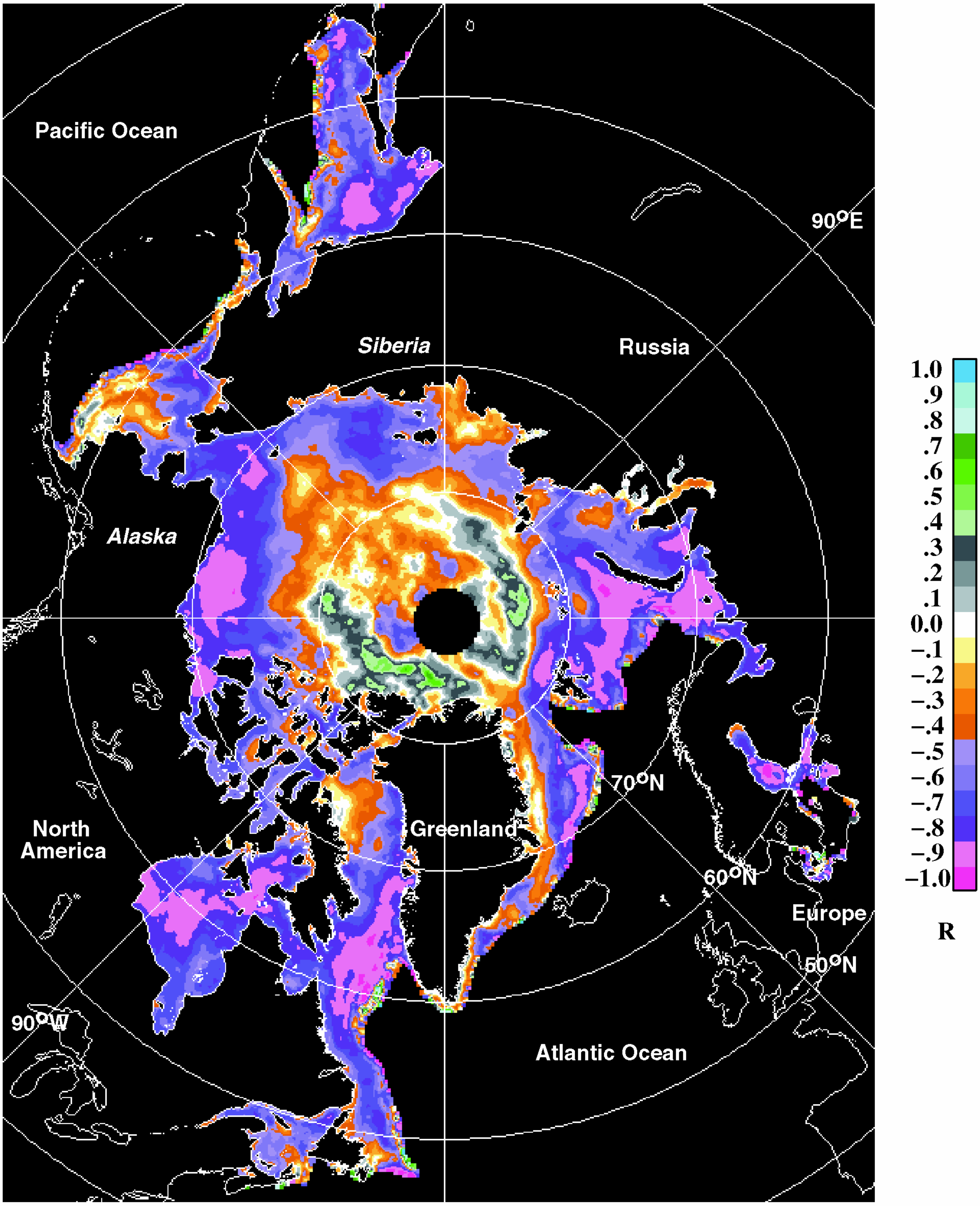

Fig. 5. Correlation map of ice-concentration and surface-temperature anomalies using yearly anomalies 1981–2000.

Thus, even if the trend in areal extent is zero, the overall ice-cover thickness could be reduced.

We postulate that during the 7 year period 1991–97 the ice cover thinned significantly due to this phenomenon. The time period coincided with some of the submarine cruises during the Scientific Ice Experiments (SICEX) program that yielded draft data used for the detection of ice thinning by Rothrock and others (1999). If verified, this technique could be a powerful tool for thickness-trend studies since it provides global and spatially detailed coverage.

Trend analysis of the perennial sea-ice cover produces intriguing results. Linear regression analysis of the ice-minimum data shows unusually large negative trends in both extent ($-6.7 \pm 2.4\%$ dec^{-1}) and ice area ($-8.3 \pm 2.4\%$ dec^{-1}). Together with previous results, this means a negative change in both area and thickness and hence volume. A reduction in surface area is a natural consequence of a thinning ice cover since under similar environmental conditions it is the thinner ice type that is melted first during the summer period. For comparison, similar analyses using data during maximum extents for each year yielded trends in ice extent and ice area of $-1.33 \pm 0.59\%$ dec^{-1} and $-1.85 \pm 0.58\%$ dec^{-1}, respectively. The much lower trends from winter maximum data again made the overall trends low compared to those of the perennial ice cover.

The monthly averages in surface temperature for each

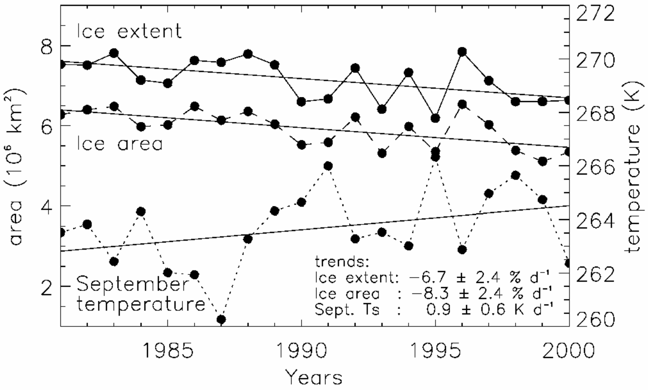

Fig. 6. Yearly ice extents and actual ice areas of the perennial ice cover, 1981–2000, represented by values during summer minima, the date of which is determined using a 7 day running average of the daily extents. Also plotted are monthly average summer ice temperatures (sea-ice concentration >80%) in September of each year 1981–2000. The results from linear regression of each dataset are as indicated.

September (when ice minima usually occur) from 1981 to 1999 are also shown in Figure 6. The surface temperatures are taken from areas with sea-ice concentrations of 80% and higher. A higher minimum concentration is not used because errors in concentration can be as large as 20% during this time period when the surface is melt-ponded and/or wet. Overall, the time series reveals an unusually large warming trend of 0.9 ± 0.6 K dec^{-1} during the 1981–99 period. This is a high rate of warming compared with those derived from the continuous dataset of monthly anomalies or yearly averages (0.4 K dec^{-1}) and could partly explain the high negative trend in the ice cover.

The yearly fluctuation is very well correlated with those of ice extent and ice area, with a correlation coefficient of about 0.65. Thus, when the temperature was abnormally high as in 1995, the ice extent and ice area were abnormally low, whereas, when the temperature was abnormally low, as in 1996, the ice extent and ice area were abnormally high. There are some exceptions, such as in 1987/88 and 1990/91 when warming is accompanied by increases in extent and ice area, but this may signify that more complex processes sometimes affect the variability in the ice cover. It is useful to know that there is such a strong relationship between the two variables.

DISCUSSION AND CONCLUSIONS

Co-registered satellite ice-concentration and surface-temperature data for the period 1981–2000 have been assembled and analyzed, and this study shows that simultaneous observation of the two parameters provides useful knowledge about the changing Arctic. Ice-concentration data provide physical characterization of sea-ice spatial distributions, while surface temperatures provide information about the thermal state of the ice surface. Each dataset provides independent evaluation of the changing state of the Arctic, but together they provide a more complete characterization.

A general assessment from the monthly and yearly data shows that ice extent has been declining at a rate of 2.3% dec^{-1} while surface temperature has increased by 0.4 K dec^{-1}. This rate of decline is smaller than the 2.8% dec^{-1} previously reported, but that value was for a different period (1978–96) and a different ice-concentration algorithm was utilized to generate the ice dataset.

The yearly anomalies in both ice concentration and temperature provide new insights into the changing Arctic ice environment. They provide year-to-year changes in good spatial detail of sea-ice distributions, and specific locations and magnitude of large positive and negative anomalies. The data show that positive anomalies in ice concentrations predominate in the 1980s, while the reverse is true in the 1990s. This indicates that the ice cover has been declining. Similarly, negative anomalies in surface temperatures were dominant in the 1980s, while positive anomalies were more frequent in the 1990s. This shows that while the ice cover is declining, the surface temperature is rising, indicating a close linkage of the two variables.

The yearly temperature-anomaly maps provide useful information that is not available from the sea-ice-cover data. These maps show that there are large anomalies in the Arctic that extend beyond the sea-ice margins. They allow quantification of the scope of these anomalies which are apparently driven by atmospheric patterns. The coherence of the spatial distribution of the anomalies of ice concentration and surface temperature is quite good, and quantitative analysis shows high negative correlation of the two variables, especially in the seasonal ice regions where the anomalies are abnormally high. It is also apparent that there were some years when the anomaly patterns were exceptionally high, such as 1998, which is regarded as the warmest year in the 20th century. High positive anomalies are indeed evident in the 1997/98 and 1998/99 ice seasons, but they are confined primarily to the Beaufort Sea and North America, while slight cooling occurred in Russia and the Kara Sea.

To better understand the current state of the Arctic ice cover, a good quantification of the variability of the perennial ice cover is required, derived from analysis of the extents and areas of the ice cover during summer minimum. Results show that the Arctic summer ice extent and area have been declining at a rate of -6.7 ± 2.4% dec^{-1} and -8.3 ± 2.4% dec^{-1}, respectively, while the average September surface temperature values increased by 0.9 ± 0.6 K dec^{-1}. The rate of decline in the perennial ice cover is more than twice the rate of decrease in total sea-ice cover. The rate of increase in surface temperature in September is also surprisingly high and more than double that for all seasons. These are significant results since they pertain to the perennial ice cover which is directly connected to the ice-thickness distribution. In addition, the minimum extent shows higher yearly fluctuations in the 1990s than in the 1980s. Even without a trend, such a phenomenon would cause a change in the overall composition of the different ice types, and favors increases in the fraction of the thinner, younger ice cover (e.g. second-year ice), compared with the older, thicker ice types. The large fluctuation in the areal coverage of the perennial ice cover may thus be accompanied by a decrease in ice thickness.

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