A Rapidly Declining Arctic Perennial Sea Ice Cover

J. C. Comiso

Ocean and Ice Branch, Code 971

NASA Goddard Space Flight Center

Greenbelt, MD 20771

Abstract

The perennial sea ice cover in the Arctic is shown to be declining at -8.9 ± 2.0 % per decade, using 22 years of satellite data. A sustained decline at this rate would mean the disappearance of the multiyear ice cover during this century and drastic changes in the seasonal characteristics of the Arctic ice cover. An apparent increase in the fraction of second year ice in the 1990s is also inferred suggesting an overall thinning of the ice cover while co-registered satellite surface temperatures show a warming trend of 0.8 ± 0.6 K per decade in summer and a good correlation with the perennial ice data.

1. Introduction

The sea ice cover in the Northern Hemisphere has been reported to be on the retreat by about 3% per decade, using satellite data from 1979 through 1996 *(1, 2)*. Significant thinning in the ice cover has also been observed by several investigators *(e.g., 3, 4, 5)* using five decades of submarine draft data. Moreover, the sea level pressure has been shown to be declining during the last 4 decades *(6)* while hydrographic measurements have suggested a warming for water masses below the halocline *(7)*. Other studies done in conjunction with physical numerical models have indicated that the

Arctic region may already be experiencing some profound changes *(8, 9, 10)* and may be an environment in transformation *(11)*. Nevertheless, further studies are needed because of large uncertainties in some of the measurements and the complexity of the Arctic climate system.

The Arctic sea ice cover has been noted as basically impenetrable because of the dominant presence of the perennial ice cover that consists mainly of multiyear ice, the average thickness of which is about 3 meters *(12)*. These thick multiyear ice floes are the major component of the Arctic climate system and what is uniquely the Arctic sea ice cover as we know it today. These floes survive the summer melt mainly because of a strongly stratified Arctic Ocean that is in part responsible for the scarcity of convection in the region *(13)*. In this paper, the variability of the perennial sea ice cover, which is defined as the ice cover during minimum extent, is studied to gain insights into the changing characteristics and composition of the sea ice cover in the Arctic. Sensitivity and comparative analyses with other data are also performed to demonstrate that the trend results are credible and can be consistently derived.

2. Satellite Observations of the Arctic Sea Ice Cover

Multichannel passive microwave satellite observations have provided almost continuous data on global sea ice cover since the launch of the Scanning Multichannel Microwave Radiometer (SMMR) in October 1978 which was followed by the Special Sensor Microwave/Imager (SSM/I) in July 1987 *(2,14)*. This study makes use of results from analysis of ice data from October 1978 to August 2001. The monthly and interannual variations in the Arctic sea ice extent and area during this period are shown in

Figures 1a and 1b, with the seasonal variability subtracted. Large interannual variations are apparent, the most remarkable of which is the big drop in extent and area in 1995 followed by a recovery in 1996. Linear regression of the data yielded trends in ice extent and area of -2.0 ± 0.2 %/decade and -3.0 ± 0.2 %/decade, respectively. The trends in the ice extent and the ice area are slightly different and mainly due to a declining monthly average ice concentration of about -1.25 ± 0.10 %/decade (Figure 1c). Such a decline may be caused by more divergence due to increasing rate in storm occurrences in the region as can be caused by the changing sea level pressure *(6)*. The updated results, which makes use of a different technique for deriving sea ice concentration *(15)*, are in general agreement with previous observations *(1, 2)* and indicate a continuation of the general decline in the ice extent and ice area.

To gain a better understanding of the trend results, we examine the ice cover changes of the extents and ice areas on a season-by-season basis as presented in Figures 2a and 2b. The plots show negative trends for all seasons with the biggest change occurring in the summer at -4.1 ± 0.9 %/decade in the ice extent followed by autumn at -2.7 ± 1.3 %/decade. The trends in ice area are again greater at -6.0 ± 1.1 %/decade in summer and -3.9 ± 1.2 %/decade in autumn. A reduction in the summer ice cover means that there is more open water in the region exposed to sunlight, which in turn means that more heat energy is absorbed by the Arctic surface water *(16)*. The latter would cause a delay in the onset of freeze up and may explain the relatively high negative decline in the ice cover in autumn. The negative trends in both summer and autumn are manifestations of a declining perennial ice cover as discussed in the following sections.

3. Spatial Variability in the Perennial Sea Ice Cover

The microwave signature of multiyear ice has been observed to be significantly different from that of first year ice *(14)*. This information has been used to study the ice cover characteristics in terms of different ice types *(11, 14)*. Large variations in the emissivity of multiyear ice in the Arctic, however, have been observed *(17)* causing inaccurate assessments in the fraction of multiyear ice not only in the Central Arctic but also in the peripheral seas where they are not expected *(18, 19)*. The key to a more accurate quantification of the multiyear ice cover is through the use of the information that during minimum extent, the seasonal sea ice cover has basically melted and what is left is what we call the perennial ice cover made up mainly of multiyear ice floes *(18)*.

To provide an overview about interannual variations in the spatial distribution of the perennial ice cover, color-coded ice concentration maps during the summer minimum from 1979 to 2000 are shown in Figure 3. The day of minimum extent for each year is determined through the use of seven-day running mean data of ice extents. The running mean is used to maximize the chance that what is chosen is the date of real minima and not what might be the result of a temporary compaction due to wind forcing. The dates are mainly in the second or third week of September (Figure 3) and are found to be consistent within a few days with those of ice area minimum.

The images in Figure 3 provide a means to qualitatively identify the relative location of the thick multiyear ice cover at the end of each ice season. Open water is represented by blue in the images and is shown to vary in area from one year to the next around the periphery of the Arctic basin. The circular areas in black are areas not covered by the satellite sensors. The location of the perennial sea ice cover (see Figure 4 for location map) depends on many factors, the most important of which the advection characteristics of the ice floes. The drift of the ice cover has been shown to be strongly influenced by atmospheric circulation which is sometimes cyclonic and other times anti-cyclonic *(20)*. During the cyclonic mode the ice is usually advected to the west causing large open water areas in the east (e.g., Laptev and Kara Seas) and relatively small open areas in the west (e.g., Beaufort Sea and Chukchi Seas). During anti-cyclonic mode, the opposite scenario occurs. Examination of the images in Figure 3 indeed indicates that there are periods of large open water in the east and periods of large open water in the west. However, it is evident that the type of circulation mode cannot be easily inferred from the images, partly because the mode is sometimes not consistently the same (with wind changing directions) duringt the year.

In general, however, the areas of highest open water variability are either in the eastern side (e.g., Siberian and Laptev Seas) or the western side (e.g., Beaufort and Chucki Seas). During some years, large open ocean areas (in blue) are exposed in the Siberian and Laptev Seas (i.e., 1981, 1982, 1983, 1989, 1990, 1991, 1993, 1995, 1999, 2000) while during other years, the large open ocean areas are in the Beaufort and Chucki Seas (1990, 1993, 1995, 1997, 1998, 1999). It is apparent that there are many more large openings in the 1990s than in the 1980s. The exception is 1996 which has anomalously high ice extent at the end of the ice season.

To obtain an overview of changes from one decade to another, Figure 4a shows the average ice concentration using the ice minimum maps from 1979 to 1989 while Figure 4b shows a similar average from 1990 to 2000. It is apparent that the size of the ice cover in the latter period is smaller than that of the earlier one and that much of the changes occur around the ice margin. To quantify the changes from one decade to another, a difference map between the two ice concentration maps is presented in Figure 4c. This map shows the magnitude and location of the changes with the negative changes represented by yellows, oranges, purple and reds while positive changes are in grays, greens, and blues. The decadal change is quite substantial and mainly negative with the net change in extent and ice area being 5.1 x 10^5 km^2 (6.2%) and 6.9 x 10^5 km^2 (11.0%), respectively. The biggest change occurred in the western ;area (Beaufort and Chukchi Seas) while considerable changes are also apparent in the eastern region (Siberian, Laptev and Kara Seas). There are some positive changes but are mainly in the vicinity of Greenland and the areal coverage is small by comparison.

4. Trends in the Perennial Sea Ice Cover

Three techniques were used for deriving the extent and area of and trend in the perennial ice cover, all providing consistent results. The first one makes use of the data during minimum extent in the entire Arctic, as in Figure 3. The two other techniques address the concern that the ice cover minimum does not occur at the same time in different areas. The second technique divides the Arctic into three sectors along longitudinal lines with 120° separation. The minimum ice cover for each year is determined separately in each sector and the results were combined to obtain yearly values of both ice extent and ice area. The third technique uses a similar procedure but smaller sectors with 30° longitudinal separation. The resulting minimum extents and areas from these techniques are presented in Figure 5a and 5b, respectively, with the results from the first in bold lines, the second in dash lines, and the third in dotted lines.

It is apparent that the values from the three are all coherent and consistent, with the third showing slightly lower values than the others. The regression lines are also plotted and the perennial sea ice cover is shown to be declining at a relatively large negative rate, independent of technique. The first technique shows a decline of -6.4 ± 2.1 % per decade and -8.5 ± 2.0 % per decade for extent and actual area, respectively, during the 1979 to 2000 period. The second and third techniques yielded trends in ice extent of -6.3 ± 2.1 and -6.6 ± 2.3 %/decade, respectively. The corresponding trends in ice area are -9.1 ± 2.0%/decade and -9.2 ± 2.2%/decade.

If the ice cover is stationary, the desired technique of the three would be the one that uses the 30°-sector since it does the best job in accounting for regional effects. However, we know that the ice fields are not stationary and ice can be advected from one sector to another even within a few days. Also, with the multiple sectors, the ice edges do not necessarily match at the sector boundary. There is, however, a general consistency in the results suggesting that these effects are not large. The averages of the three are taken as the most likely values and are used as our estimate of the extents and areas of the perennial ice cover, as presented in Figures 6a. The trend results from these averages are -6.4 ± 2.2 %/decade and -8.9 ± 2.0 %/decade for ice extent and ice area, respectively. The 90% confidence level for the trend in ice extent lies between -2.6 and -10.2 % per decade while for the area the confidence level for the trend is between -5.4 and -12.4% per decade. The observed trend in area is larger but consistent (within these limits) to the 7% per decade decrease in the multiyear ice cover as reported previously *(11)*. This implies that the known bias and error in the multiyear ice data *(19)* may be relatively constant with time, and hence the general agreement. Our result provides an independent and a more compelling evidence of an Arctic ice cover in transformation. It is also consistent (within the same limits) to the 11% change in area from the 1980s to the 1990s as presented in the previous section.

It is intriguing to note that the perennial sea ice cover has much greater yearly fluctuations with a standard deviation of about 20% in the 1990s compared to less than 10% in the 1980s. Increases in the extent (e.g., 1991 to 1992, 1993 to 1994, and 1995 to 1996) are caused only by increases in the fraction of second year ice floes while decreases in extent (1989 to 1990, 1992 to 1993, 1994 to 1995, and 1996 to 1998) are caused by the melt of both second year and older and thicker ice types. For example, during the big change in area from 1995 to 1996, there was a 24% increase in the fraction of second year ice. If we assume that the percentage of second year ice was 20% per unit area in 1995, we estimate that this percentage would increase to 36% in 1996. This by itself can translate to a significant decrease in the average thickness of ice within a given area from 1995 to 1996. The larger fluctuations of perennial ice cover in the 1990s than in the 1980s thus suggest a general thinning in the ice cover. This may in part be associated with the reported decrease in ice thickness *(3, 4)* in which submarine ice draft data in the 1990s were compared with those of previous decades. It is interesting to note that no changes in sea ice thickness in the 1990s were observed *(21)* but this may be partly due to the limited sampling (in time and space) provided by the submarine data.

Studies of Arctic surface temperatures derived from satellite infrared data reveal that anomalously warm temperatures are more prevalent during recent years compared to earlier ones, especially in the Beaufort and Chukchi Sea regions *(22)*. To gain insights into the declining perennial ice cover, the same (but extended) data set used in *(22)* is analyzed with emphasis on the temperature variability during the summer (June, July, and August) and early autumn (September). The temperature averages, shown in Figure 6b, indicate large temperature fluctuations for both summer and early autumn. The temperatures are not always coherent during both periods reflecting seasonal variations. The results of regression analysis, however, yielded similar warming trends of 0.8 ± 0.6 and 0.8 ± 0.7 °C per decade for summer and early autumn, respectively. This is consistent with an amplification in the Arctic of the global warming previously reported *(23)* and agrees qualitatively with in situ observations *(24)*. It is apparent from the plots that surface temperatures, especially during summer, are coherent with the extent and area of the perennial ice cover. Comparative statistical analyses yielded good correlations with a correlation coefficient of -0.68 between ice extent and temperature and -0.69 between ice area and temperature for the summer data. The corresponding correlation values are -0.60 and -0.54 for the early autumn data. The good correlations, especially in the summer, confirm previous results showing that variabilities in surface air temperature in the Arctic lead to a high degree to variabilities in surface melt and therefore in ice thickness *(25)*. In simplified terms, warmer temperatures during the summer causes surface melt to occur earlier which in turn causes ice to get thinner or melt completely. As the ice retreats, more open water is exposed to solar heat that would inhibit the onset of freeze up the following autumn. This in effect causes a thinner ice cover in subsequent winter and the cycle continues. A correlation of -0.69 means that 48% of the variance can be attributed to a linear relationship between the two variables. The correlation between the two is not any stronger because of complications by other factors such as the ever changing atmospheric circulation and ice advection characteristics. For example, a cooling might be accompanied by advection of ice to warmer waters where they melt readily while a warming can occur concurrently with advection of ice to the north where they don't melt completely.

5.0 Discussion and Conclusions

The area of the Arctic perennial sea ice cover is shown to be declining at a relatively fast rate of 8.9 ± 2.0 % per decade. The ice area from an 11-year average of the perennial ice data from 1990 to 2000 is also shown to have shrunk by 11% when compared to that of the 1979 to 1989 average. If such rate of decline persists for a few more decades, the perennial sea ice cover will likely disappear within this century. The decline is unlikely linear because of positive feedback effects between ice, ocean, and the atmosphere. For example, as the summer ice cover retreats further north, more solar heat gets absorbed by more open water, and more ice gets melted by a warmer upper water layer. This causes delays in onset of freeze up that leads to a thinner ice cover overall that is more vulnerable to melt the subsequent summer. Furthermore, a positive trend in the ice temperature of about 0.8 K per decade is also observed leading to earlier onset of melt and delayed onset of freeze up that in turn causes further thinning and retreat of the perennial ice cover.

The implications of a disappearance of the perennial ice cover are many and can be profound. It would mean a completely different albedo for the Arctic during the summer and a completely different ice-ocean-atmosphere feedback. It would mean a much larger influx of solar radiation into the Arctic Ocean thereby changing the characteristics of the mixed layer and the stratification of the ocean. The seasonality and characteristics of the ice cover in the region would be very different. The climate, the productivity, and biota in the region will change tremendously while the region becomes more accessible to human activities.

It should be pointed out, however, that the satellite data record is relatively short. The Arctic system is also a complex system controlled by many variables and influenced by unpredictable events (e.g., volcanic eruptions, ENSO). There are also periodic cycles, such as the Arctic Oscillation and the North Atlantic Oscillation *(26)*, and the associated decadal and inter-decadal changes in pressure and atmospheric circulation could cause a decadal variability in the ice cover. Nevertheless, because of the magnitude in the observed rate of decline and associated feedback effects, a near term recovery is likely needed to avoid an irreversible change in the Arctic ice cover and its environment.

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1. (a) montly ice extent anomalies from 1978 to 2001; (b) monthly ice area anomalies from 1978 to 2001; (c) monthly ice concentrations from 1978 to 2001. The line in

gray are 3-year running averages. Dash lines are results of linear regression fits. The anomalies are derived by subtracting the 1978 to 2001 averages from each monthly average.

2. (a) ice extent averages and (b) ice area averages for winter, spring, summer, and autumn from 1978 to 2001. The dash lines are results of linear regression fits.
3. Color-coded daily ice concentration maps in the Arctic during ice extent minima for each year from 1979 to 2000.
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6. Plots of (a) ice extent and area of the perennial ice cover from 1979 through 2000; and (b) surface ice temperatures (with ice concentration > 80%) during summer (June, July, and August) and early autumn (September) from 1981 through 2000.

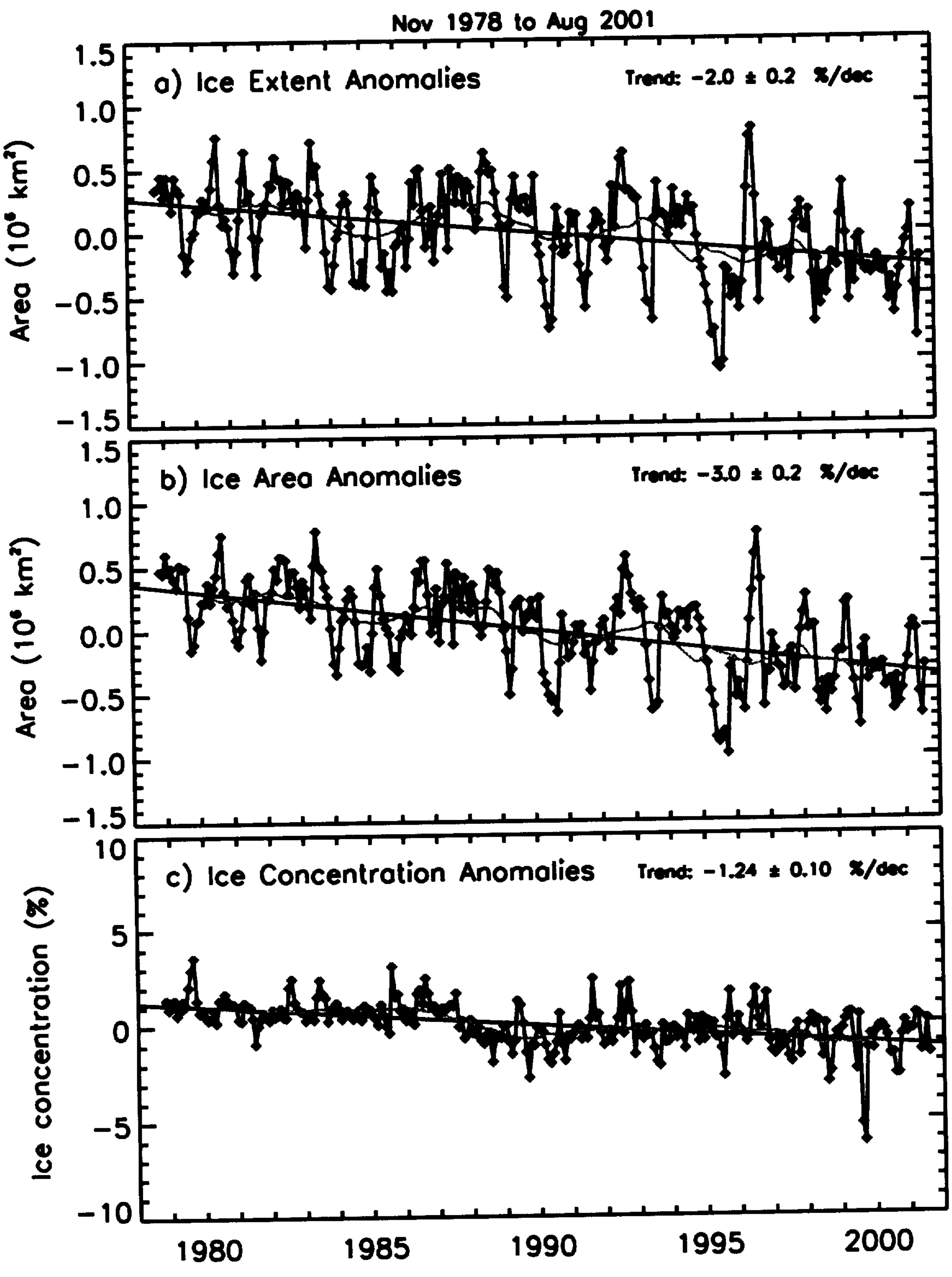
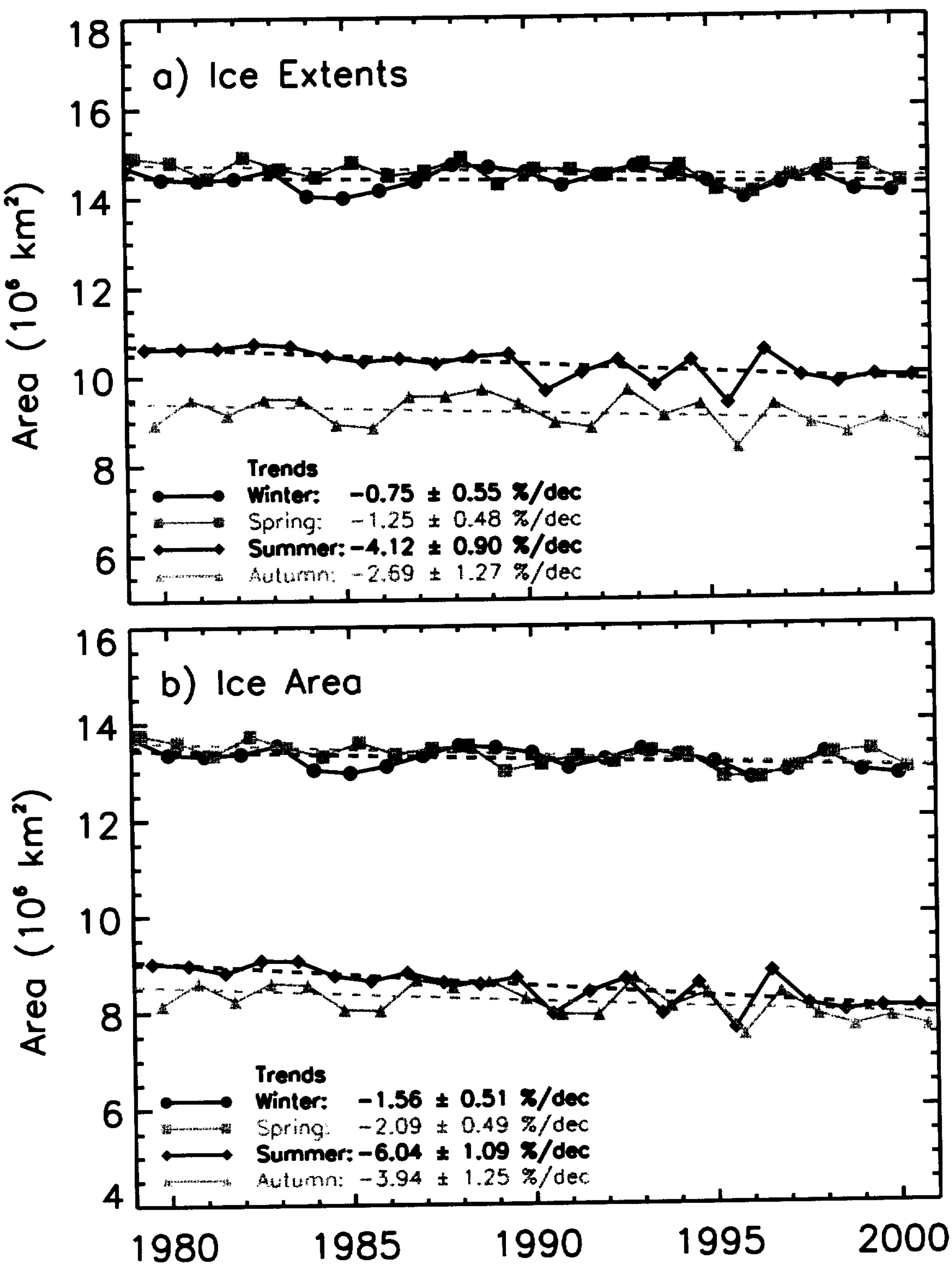

Nov 1978 to Aug 2001
a) Ice Extent Anomalies
Trend: −2.0 ± 0.2 %/dec
Area (10^6 km^2)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
b) Ice Area Anomalies
Trend: −3.0 ± 0.2 %/dec
Area (10^6 km^2)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
c) Ice Concentration Anomalies
Trend: −1.24 ± 0.10 %/dec
Ice concentration (%)
10
5
0
−5
−10
1980
1985
1990
1995
2000

Figure 1



a) Ice Extents
Area (10^6 km^2)
18
16
14
12
10
8
6
Trends
Winter: −0.75 ± 0.55 %/dec
Spring: −1.25 ± 0.48 %/dec
Summer: −4.12 ± 0.90 %/dec
Autumn: −2.69 ± 1.27 %/dec
b) Ice Area
Area (10^6 km^2)
16
14
12
10
8
6
4
Trends
Winter: −1.56 ± 0.51 %/dec
Spring: −2.09 ± 0.49 %/dec
Summer: −6.04 ± 1.09 %/dec
Autumn: −3.94 ± 1.25 %/dec
1980
1985
1990
1995
2000

Figure 2

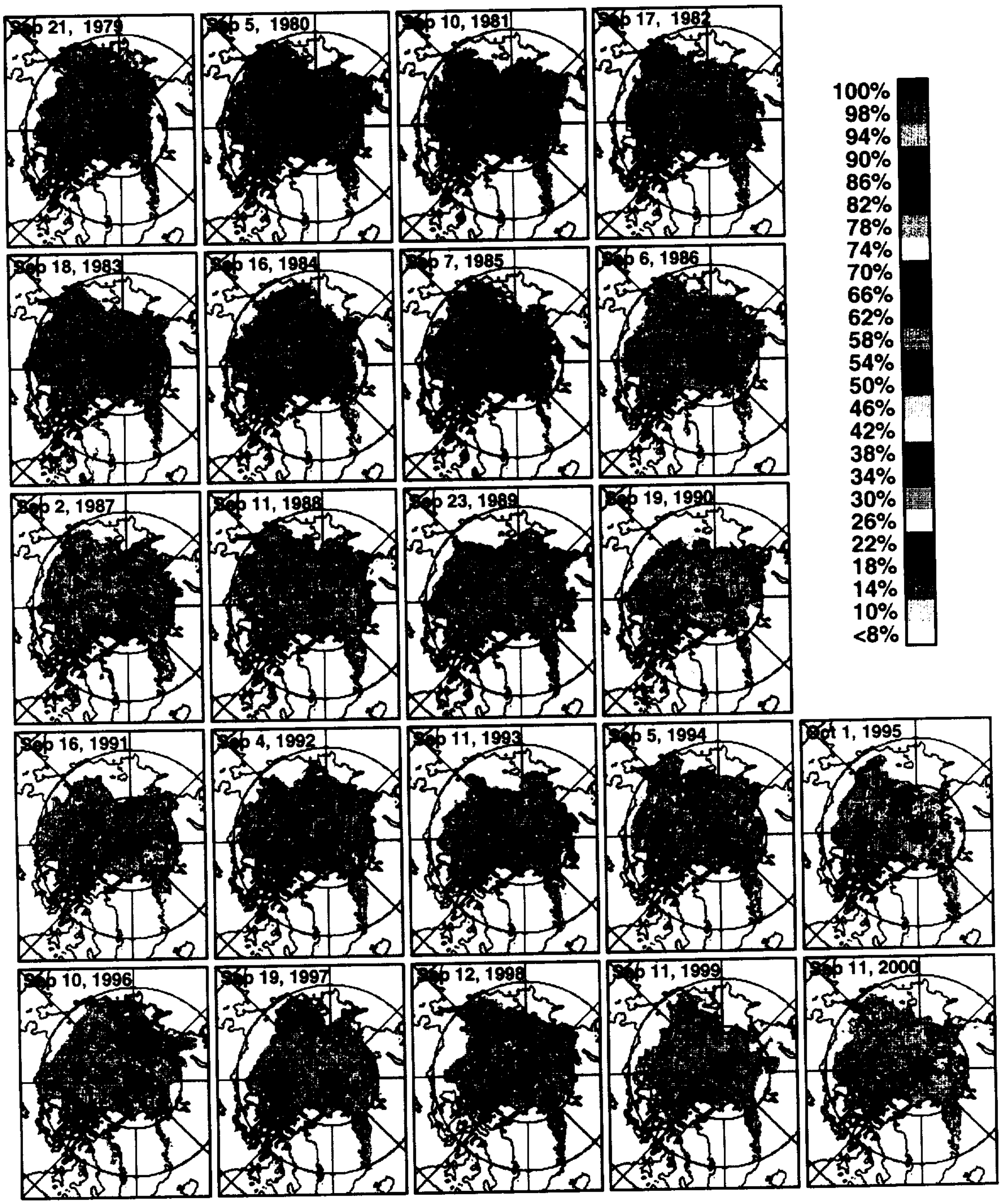

Sep 21, 1979
Sep 5, 1980
Sep 10, 1981
Sep 17, 1982
Sep 18, 1983
Sep 16, 1984
Sep 7, 1985
Sep 6, 1986
Sep 2, 1987
Sep 11, 1988
Sep 23, 1989
Sep 19, 1990
Sep 16, 1991
Sep 4, 1992
Sep 11, 1993
Sep 5, 1994
Oct 1, 1995
Sep 10, 1996
Sep 19, 1997
Sep 12, 1998
Sep 11, 1999
Sep 11, 2000
100%
98%
94%
90%
86%
82%
78%
74%
70%
66%
62%
58%
54%
50%
46%
42%
38%
34%
30%
26%
22%
18%
14%
10%
<8%

Figure 3

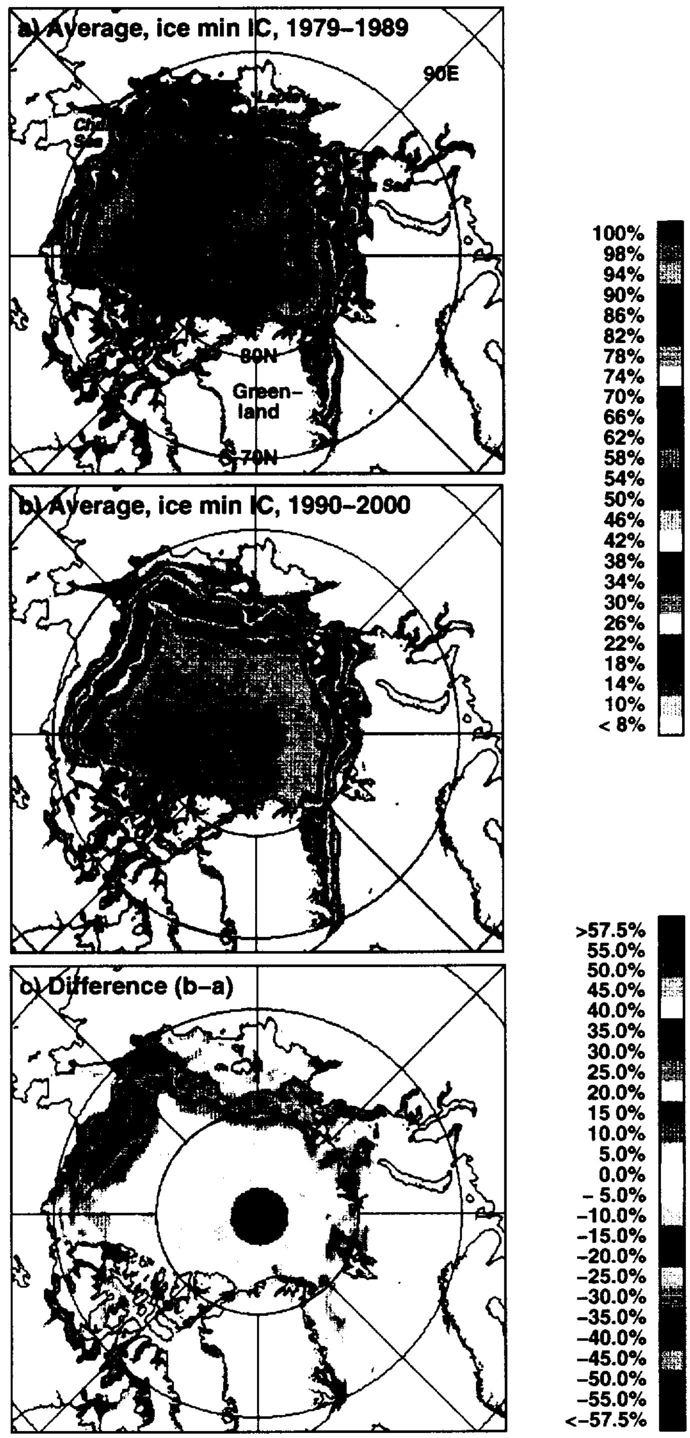
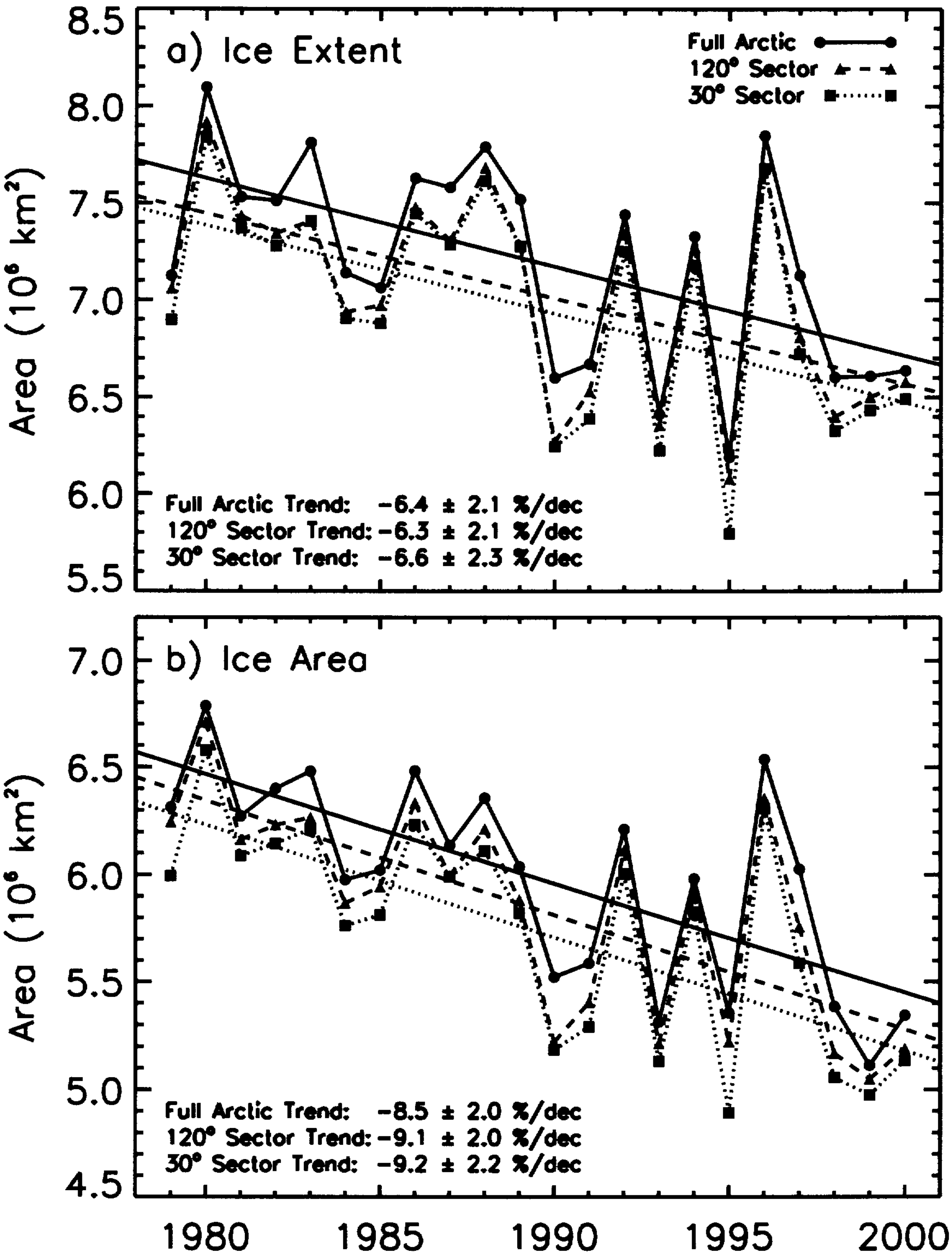

a) Average, ice min IC, 1979–1989
90E
80N
Green-
land
70N
b) Average, ice min IC, 1990–2000
c) Difference (b–a)
100%
98%
94%
90%
86%
82%
78%
74%
70%
66%
62%
58%
54%
50%
46%
42%
38%
34%
30%
26%
22%
18%
14%
10%
< 8%
>57.5%
55.0%
50.0%
45.0%
40.0%
35.0%
30.0%
25.0%
20.0%
15 0%
10.0%
5.0%
0.0%
- 5.0%
-10.0%
-15.0%
-20.0%
-25.0%
-30.0%
-35.0%
-40.0%
-45.0%
-50.0%
-55.0%
<-57.5%

Figure 4



a) Ice Extent
Full Arctic
120° Sector
30° Sector
Area (10^6 km^2)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
Full Arctic Trend: -6.4 ± 2.1 %/dec
120° Sector Trend: -6.3 ± 2.1 %/dec
30° Sector Trend: -6.6 ± 2.3 %/dec
b) Ice Area
Area (10^6 km^2)
7.0
6.5
6.0
5.5
5.0
4.5
Full Arctic Trend: -8.5 ± 2.0 %/dec
120° Sector Trend: -9.1 ± 2.0 %/dec
30° Sector Trend: -9.2 ± 2.2 %/dec
1980
1985
1990
1995
2000

Figure 5

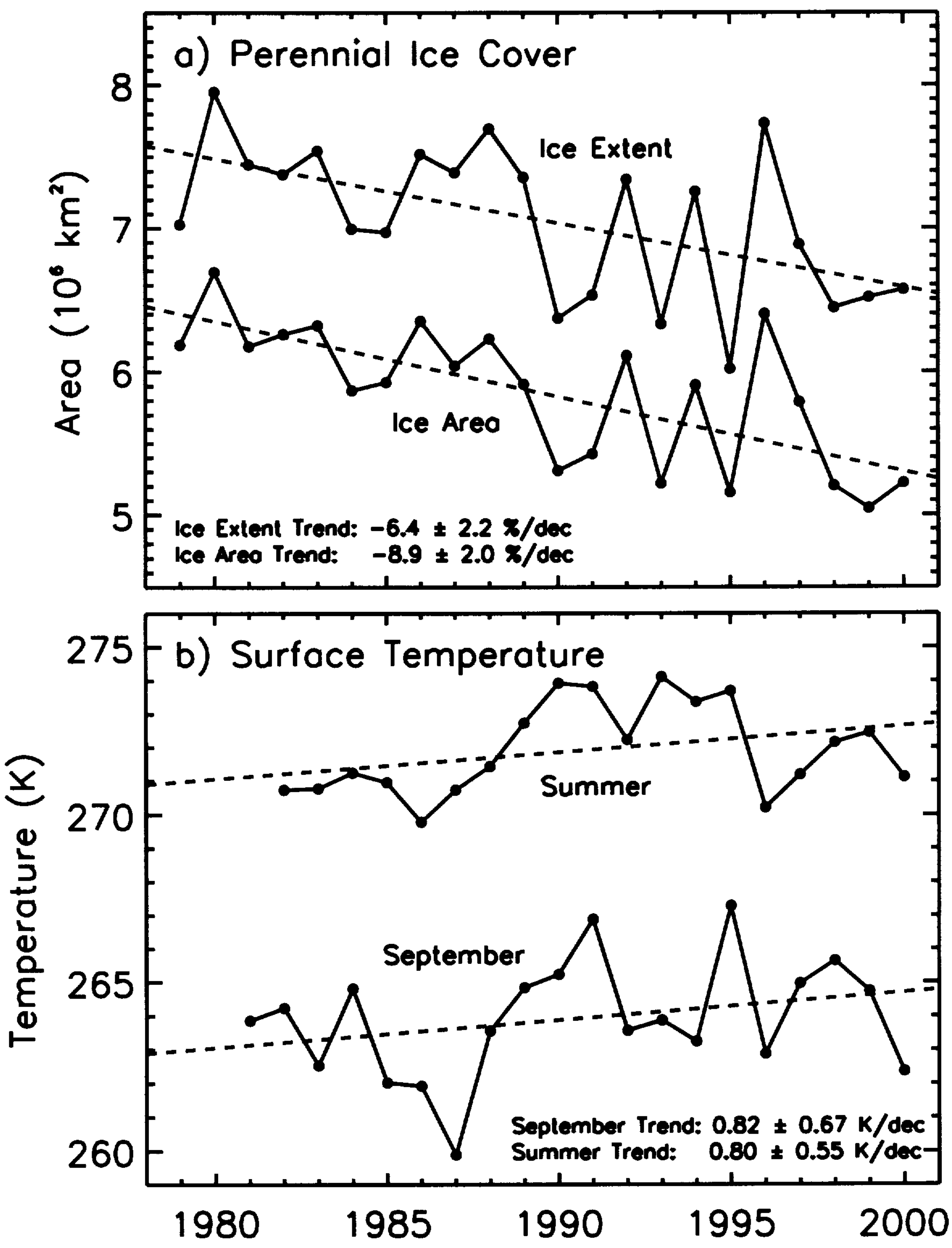

a) Perennial Ice Cover
Ice Extent
Ice Area
Area (10⁶ km²)
Ice Extent Trend: −6.4 ± 2.2 %/dec
Ice Area Trend: −8.9 ± 2.0 %/dec
b) Surface Temperature
Summer
September
Temperature (K)
September Trend: 0.82 ± 0.67 K/dec
Summer Trend: 0.80 ± 0.55 K/dec
8
7
6
5
275
270
265
260
1980
1985
1990
1995
2000

Figure 6