A rapidly declining perennial sea ice cover in the Arctic

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[1] The perennial sea ice cover in the Arctic is shown to be declining at −9% per decade using satellite data from 1978 to 2000. A sustained decline at this rate would mean the disappearance of the multiyear ice cover during this century and drastic changes in the Arctic climate system. An apparent increase in the fraction of second year ice in the 1990s is also inferred suggesting an overall thinning of the ice cover. Surface ice temperatures derived from satellite data are negatively correlated with perennial ice area and are shown to be increasing at the rate of 1.2 K per decade. The latter implies longer melt periods and therefore decreasing ice volume in the more recent years. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 1635 Global Change: Oceans (4203); 1640 Global Change: Remote sensing. **Citation:** Comiso, J. C., A rapidly declining perennial sea ice cover in the Arctic, *Geophys. Res. Lett.*, *29*(20), 1956, doi:10.1029/2002GL015650, 2002.

1. Introduction

[2] 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 3–4 meters [*Wadhams and Comiso*, 1992]. The thick multiyear ice floes are the major components of the current Arctic sea ice cover. Their presence during the peak of summer makes a big difference in the ocean-ice-albedo feedback because of their vast extent and high albedo. They 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 [*Aagard and Carmack*, 1994]. A study of the perennial ice cover is of immense practical importance because of the potential impact not only on climate but also on the environment and ecology of the system and in light of recent reports of ice retreat [*Bjorgo et al.*, 1997; *Parkinson et al.*, 1999] and ice thinning [*Rothrock et al.*, 1999; *Wadhams and Davis*, 2000].

[3] In this paper, the state of the perennial sea ice cover is studied using satellite passive microwave data from 1978 through 2000. The multiyear ice cover has been inferred from passive microwave data in winter using a technique that assumes that the signature is spatially stable during this period [*Johannessen et al.*, 1999]. However, previous studies have indicated large regional variations in the passive microwave signature [*Grenfell*, 1992] causing substantial biases in the derived fraction of multiyear ice within the pack [*Kwok et al.*, 1996]. The key to a more accurate quantification of the multiyear ice cover is through the use of data during minimum extent since at this time, the seasonal sea ice cover has basically melted and what is left is what we call the perennial ice cover consisting mainly of multiyear ice floes [*Comiso*, 1990]. These data are also easier to quantify and interpret since no ice classification is needed.

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2. Spatial Variability in the Perennial Sea Ice Cover

[4] To provide an overview about interannual variations in the spatial distribution of the perennial ice cover, color-coded ice concentration maps during the summer ice minimum from 1979 to 2000 are shown in Figure 1. The ice concentration maps were derived from satellite passive microwave data using the Bootstrap Algorithm as described in *Comiso et al.* [1997]. Slight adjustments were made to ensure that the data set is temporally consistent using a procedure similar to that used in *Parkinson et al.* [1999]. 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 1) and are found to be consistent within a few days with those of ice area minimum.

[5] The images in Figure 1 provide a means to quantitatively identify the relative location and concentration of multiyear ice floes at the end of each ice season. The open water area (blue) around the pack is shown to vary considerably from one year to the next. The circular black areas in the middle are areas not covered by the satellite sensors but are usually highly consolidated. The general location of the perennial sea ice cover changes from one year to another and depends on many factors, the most important of which is the ice drift which has been shown to be strongly influenced by atmospheric circulation [*Thorndike and Colony*, 1982]. The latter can be in cyclonic mode in which the ice is normally 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) or in anti-cyclonic mode in which the opposite scenario occurs. Examination of the images in Figure 1 also indicates that the open water areas are generally larger in the 1990s than in the 1980s.

[6] To better illustrate the changes from one decade to another, Figure 2a shows the average of the ice concentration minimum maps from 1979 to 1989 while Figure 2b shows the corresponding 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 occurred around the ice margin. The changes from

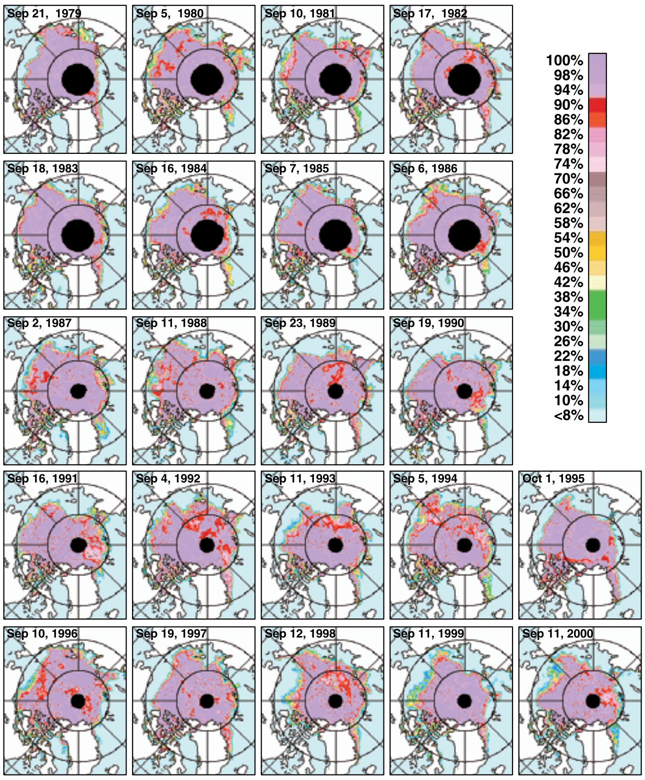

Figure 1. Color-coded daily ice concentration maps in the Arctic during ice extent minima for each year from 1979 to 2000. Each map represents the state of the perennial ice cover at the end of the ice season.

one decade to another are better quantified in the difference map (Figure 2c) between the two ice concentration maps. This map shows the magnitude and location of the changes with the negative changes represented by yellows, oranges, purples and reds while positive changes are in grays, greens, and blues. The interdecadal change is surprisingly large and intriguing with the net negative changes in extent and ice area being 5.1×10^5 km^2 (6.3%) and 6.9×10^5 km^2 (11.0%), respectively, during the 22-year period. 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). To get an idea how the ice cover may look like 5 decades from now, the decadal change as reflected in Figure 2c (but shifted towards the north) is applied to the data in Figure 2b and subsequent projections, normalized such that the change is about 10% per decade. The projected perennial ice cover for the decade of the 2050s is shown in Figure 2d. Although the technique is crude and the assumption of a linear decline is likely incorrect, Figure 2d provides a means to assess how the perennial ice cover could look like if the decline persists. It is important to note that the Arctic is governed by complex processes including a positive ice-ocean-atmosphere feedback and decadal as well as interdecadal variability including that associated with the Arctic Oscillation (AO) as described by [*Thompson and Wallace*, 1998]. A simple regression analysis of AO indices with the perennial ice area indicates that the relationship between these two variables is relatively weak with the correlation coefficient being only 0.20. The link is likely stronger if continuous ice cover data are analyzed in conjunction with the AO but such study is not within the scope of this paper.

3. Trends in the Perennial Sea Ice Cover

[7] In addition to the technique described previously to quantitatively assess the perennial ice cover, two other techniques are used to address the concern that the ice cover minimum does not occur at the same time in different regions. 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 procedure similar to the second but utilizing smaller sectors (with 30° longitudinal separation) to further minimize regional effects. The resulting minimum extents and areas are presented in Figures 3a and 3b, respectively, with the results from the first technique shown 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 second and third techniques providing almost the same values but slightly lower than those of the first.

[8] The results of regression analysis of the data show that the perennial sea ice cover is declining at a relatively large negative rate, independent of technique. Declines in ice extent of −6.4 ± 2.1%, −6.3 ± 2.1 and −6.6 ± 2.3%/decade, respectively, are derived for the first, second and third technique. The corresponding trends in the ice area are significantly higher at −8.5 ± 2.0%, −9.1 ± 2.0%/decade and −9.2 ± 2.2%/decade. The consistency of the results from all three techniques is encouraging. While not as robust in accounting for regional changes in the date of minimum extent as the other two, the first has its advantages

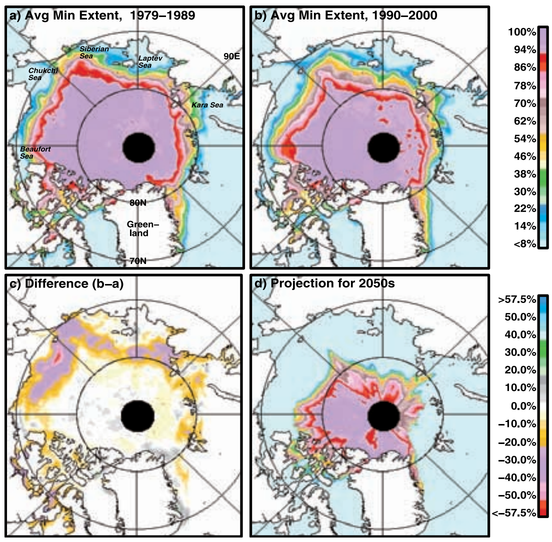

Figure 2. Color-coded averages of ice concentrations during ice minima and decadal change. (a) average of ice minima from 1979 to 1989 and (b) average of ice minima from 1990 to 2000; (c) Difference of the average ice minima in 2(b) and 2(a) and (d) projected perennial ice cover in the 2050s, assuming a linear decline reflected by 2c.

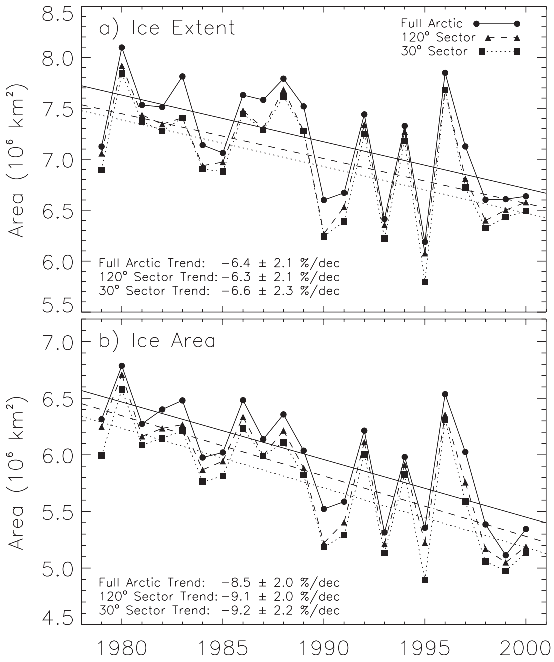

Figure 3. Yearly minimum extents and areas using the three techniques. (a) Minimum ice extents from 1979 through 2000; and (b) Minimum ice area from 1979 through 2000.

in that there are no mismatches in the location of the ice edge between sectors and the possible advection of ice from one sector to another is not a problem. In this study, the average of the three results is taken for each year, as presented in Figure 4a, and is used as the final estimate.

[9] Trend analysis of the resulting data presented in Figure 4 yielded -6.4 ± 2.2%/decade for the extent of the perennial ice cover. Further statistical analysis shows that the 90% level of confidence for the trend in ice extent lies between -2.6 and -10.2% per decade. The result for the actual perennial ice area is actually more intriguing since it shows a considerably higher declining rate of -8.9 ± 2.0%/decade. The 90% confidence level in the trend for the ice area is between -5.4 and -12.4% per decade. The observed trend in the perennial ice area is consistent with the 10% per decade change described previously and is larger than but generally consistent with the 7% per decade decrease in the multiyear ice cover as reported previously [*Johannessen et al.*, 1999]. This implies that the known bias and error in the fraction of multiyear ice cover derived from winter passive microwave data [*Kwok et al.*, 1996] is approximately constant with time. The trend for perennial ice is also much more negative than that for the entire hemisphere (i.e., -3.0% per decade) as derived using monthly anomaly data from 1978 to 2000. The latter trend is consistent with previous estimates by *Bjorgo et al.* [1997] and *Parkinson et al.* [1999] for the period 1978 to 1996.

[10] It is interesting to note that the perennial sea ice cover has much greater yearly fluctuations (20%) in the 1990s compared with those in the 1980s (10%). Increases in the extent are caused only by increases in the fraction of second year ice floes while decreases in extent 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 phenomenon by itself can cause 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 partly explain the reported decrease in ice thickness [*Rothrock et al.*, 1999; *Wadhams and Davis*, 2000].

[11] Studies of Arctic surface temperatures derived from satellite infrared data revealed that anomalously warm temperatures were more prevalent during recent years compared to earlier ones, especially in the Beaufort and Chukchi Sea regions [*Comiso*, 2001]. To gain insights into the declining perennial ice cover, the same (but extended) data set is analyzed using mainly temperature data during the summer (June, July, and August) and early autumn (September). The temperature averages during these periods, as presented in Figure 4b, indicate large fluctuations but good general agreement. The two temperature plots are not always coherent reflecting seasonal variations. The summer temperature is the more relevant of the two periods since it is the one directly associated with the observed changes in the perennial ice cover.

[12] The results of regression analysis on the temperature data yield a warming trend of 1.2 ± 0.4°C per decade in the summer and 0.6 ± 0.6°C per decade in early autumn. The magnitudes of the observed warming are consistent with

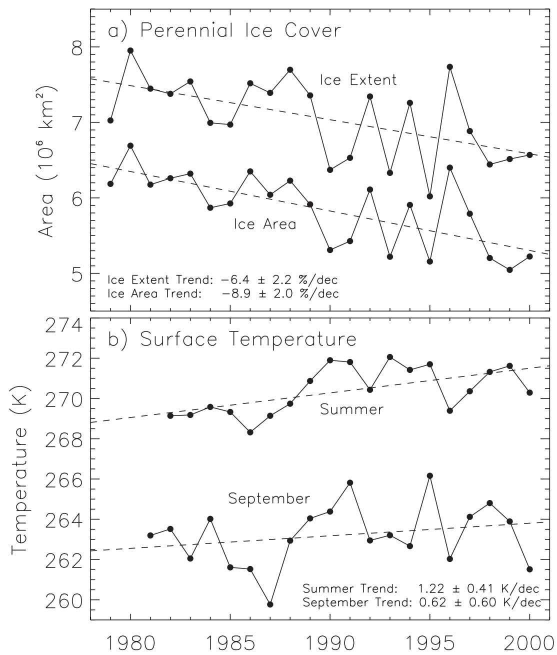

Figure 4. Perennial ice extent and area and surface temperatures. (a) Ice extent and area of the perennial ice cover from 1979 through 2000. (b) Surface temperatures over ice covered areas (with ice concentration >80%) during summer (June, July, and August) and early autumn (September) from 1981 through 2000.

those from situ observations [*Rigor et al.*, 2000; *Jones et al.*, 1999] when the same time periods for the latter are analyzed. Statistical analyses show strong correlations with the correlation coefficient being −0.77 between ice extent and temperature and −0.82 between ice area and temperature. The correlation coefficients are not any higher because of other factors such as the unpredictable effect caused by the ever changing atmospheric circulation and sea level pressure [*Walsh et al.*, 1996]. The correlation between the perennial ice extent and early autumn temperature is also good, but not as strong, the correlation coefficients being −0.60 while that between perennial ice area and autumn temperature is −0.53. The good correlation of the perennial ice cover with temperature, especially in summer, is intuitively expected and is consistent with previous modeling results indicating that variabilities in surface air temperature in the Arctic lead (to a high degree) to variabilities in surface melt and therefore in ice volume [*Hakkinen and Mellor*, 1990].

4. Discussion and Conclusions

[13] 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. A decadal change of 10% is also inferred from the difference of 11-year averages of ice minima data. If such a 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. Furthermore, a positive trend in the ice temperature of about 1.2 K per decade is 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.

[14] The implications of such a disappearance of the perennial ice cover are many and can be profound. It would mean a different albedo for the Arctic during the peak of solar insolation in summer and therefore a drastically 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.

[15] The Arctic system is however a complex system controlled by many variables and influenced by unpredictable events (e.g., volcanic eruptions). There are also periodic cycles, such as the Arctic Oscillation [*Thomson and Wallace*, 1998], the North Atlantic Oscillation [*Mysak and Venegas*, 1998] and the Pacific Decadal Oscillation [*Chao et al.*, 2000] the effects of which need to be considered. The associated decadal and inter-decadal changes in pressure and atmospheric circulation could cause a decadal variability in the ice cover that could lead to a reversal in the current trend. 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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