Abrupt Decline in the Arctic Winter Sea Ice Cover

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[1] Although the Arctic perennial ice cover has been on a rapid decline, the winter ice cover had been unexpectedly stable. We report and provide insights into a remarkable turn of events, with the observation of record low ice extent and area during the winters of 2005 and 2006. Negative ice anomalies in these years are prevalent in the peripheral seas but are most dominant in the eastern Arctic basin where the perennial ice becomes even more vulnerable to further decline. Overall, the winter ice anomalies correlates well with surface temperature anomalies and wind circulation patterns. Since historical satellite data indicate a positive trend in winter temperatures and a negative trend in the length of ice growth period it is likely that the winter ice cover will continue to retreat in the near future. Results suggest that the expected warming impact of greenhouse gases is becoming apparent in the Arctic during the dark winter months. **Citation:** Comiso, J. C. (200x), Abrupt decline in the Arctic winter sea ice cover, Geophys. Res., Lett., xx, L0000, doi:xx.xxxx/2006/GLxxxx.

1. Introduction

[2] Before 2005, the maximum extent of the Arctic winter sea ice cover as observed from satellite data has been changing modestly with the trend being negative but only about -1.5% per decade. In contrast, the Arctic perennial ice area has been declining at a rapid rate of about -10% per decade [*Comiso*, 2006]. The trend for the entire hemisphere and for all season has been modest as well being between -2 to -3 % per decade [*Bjorgo et al.,* 1997; *Parkinson et al.*, 1999]. The rapid change in the perennial ice cover, which is ice that survives at the end of the melt period, provides an intriguing signal of a warming Arctic. The perennial ice consists mainly of multiyear ice floes that have been the mainstay of the Arctic sea ice cover. The rapid decline of the ice enhances the ice-albedo feedback which in turn could accelerate the melt process [*Comiso and Parkinson,* 2004]. Although the ice was already observed to be on a rapid decline before this time [*Comiso,* 2002] the persistently low values from 2002 to 2005 had led to speculations that the sea ice cover might have reached the tipping point [*Lindsay and Zhang,* 2005] as the impact of ice-albedo feedback starts to dominate. Also, it led to postulates of a linear decline and a departure from what would be expected from the Arctic Oscillation [*Overland and Wang*, 2005]. Meantime, a near term recovery of the perennial ice cover is not apparent since surface temperature has been increasing [*Comiso,* 2006] while the ice cover in 2006 appears to be following the 2005 ice pattern.

[3] The large difference in the trends for winter maxima and summer minima was puzzling in light of the fact that greenhouse warming is supposed to be most prominent in winter [*Shindell et al.*, 1999] especially in the Arctic where long wave radiation dominates during the dark winter months. The moderate trend is also consistent with trends in surface temperatures inferred from

infrared satellite radiances during approximately the same period in winter as shown in *Serreze and Francis* [2006] who also asserted that the Arctic may be in a state of preconditioning, setting for larger changes in the years to come. In 2005, however, the winter ice cover maximum was observed to be the lowest during the satellite era and preceded the record lowest perennial ice cover during the same year. In 2006, the winter ice cover maximum was even lower than that of 2005. As in 2005, an abnormal ice retreat in the eastern region is also observed in the spring of 2006 and the seasonal trend suggests that the perennial ice area in 2006 will be anomalously low as well. In light of patterns of warming in the Arctic as has been reported recently [Comiso, 2006], these changes in the winter ice cover requires detailed study and evaluation.

2. Trends in the mid-winter and end-of-summer ice cover

[4] Two sea ice parameters that have been useful in quantifying the state of the sea ice cover are the extent and area and especially, their maximum and minimum values. Ice extent is defined as the sum of the ice covered areas with at least 15% ice concentration while ice area is the integral sum of areas actually covered by sea ice. The ice maximum extent and area provide information about available ocean surface area that is thermodynamically conditioned for ice formation during the growth season. They are in part affected by the influence of wind that causes the transport or advection of the ice cover towards the relatively warmer south. Declines in winter ice maxima would mean northward advances of the -2.0 ^{o}C sea surface temperature (SST) isotherm and therefore a warmer ocean in the region. On the other hand, the ice minimum reflects the efficiency of atmospheric and oceanic heat at melting the ice cover during the summer period. A negative trend in ice minima thus means a positive trend in oceanic and atmospheric temperatures, assuming that the percentage of ice advected out of the Arctic basin [*Kwok et al.*, 2004] is taken into consideration. The ice minimum data have been used to quantify the extent and area of the perennial ice cover [Comiso, 2002] which consist mainly of multiyear ice floes which are the mainstay of the Arctic ice cover.

[5] Analyses of passive microwave satellite data from 1978 to the present indicate significant declines in maximum and minimum ice extents and areas (Figure 1) but the minimum values have been changing about 5 times faster than maximum values. In Figure 1a, the maximum values for 2005 and 2006 stand out as significantly lower than average values and part of a monotonic decline that started in 2003 for ice extent and 2001 for ice area. The maximum extent and area observed during the satellite era were at their highest at 16.2 x 10^6 km^2 in 1990 and 15 x 10^6 km^2 in 1979, respectively, while the corresponding values for averages from 1979 to 2005 are 15.6 and 14.4 x 10^6 km^2. The maximum extents and area in 2005 are significantly lower at 14.9 and 13.5 x 10^6 km^2, respectively, while the corresponding values for 2006 are even lower at 14.6 and 13.4 x 10^6 km^2. But even with the inclusion of 2005 and 2006 data, the resulting trends in winter maximum extent and area of about -1.9 % and -2.5% per decade, respectively, are still low compared to -8.6 % and -9.6% per decade for the minimum extent and area (Figure 1b). The rapid decline of the perennial ice cover is still not well understood and may be associated with the observed reductions in average thickness in the 1990s as reported previously [*Rothrock et al.,* 1999; *Wadhams and Davis*, 2000]. The latter may have been caused by longer melt period which has been increasing at 15 days per decade [*Comiso,* 2006; *Belchansky et al*., 2004], abnormal loss of thick ice through Fram Strait [*Kwok et al.*, 2004] or higher percentages of the thinner second year ice [*Comiso*, 2002; *Comiso*, in press].

Using surface temperatures derived from satellite infrared AVHRR data during clear-sky conditions [*Comiso*, 2003], yearly winter averages (Figure1c) over all sea ice covered area (blue line) and over sea ice area north of 70°N (green line) provide the means to assess the overall effect of longwave radiation on the surface. As discussed previously, temperatures derived from AVHRR data may not represent the true surface temperature averages because of no data during cloudy conditions [*Comiso,* 2003]. The presence of clouds alters the radiation balance and causes surface temperatures over cloud-covered areas to be different from those in cloud free areas. Studies of limited data during SHEBA (1997 to 1998), however, indicated biases of only about 0.4 ^{o}C during winter months [*Comiso*, 2003]. The effect of interannual changes in cloud fraction is a concern but in part fortuitously minimized during the data processing. In particular, retrieved temperature data had to be normalized to be consistent with in situ (or station) data in order to take into account calibration inconsistencies of data from the 5 different AVHRR sensors used for the historical record. The trends in the AVHRR temperature data are thus mainly consistent with trends in the in situ data that are not biased by cloud masking.

[6] The clear-sky winter surface temperatures are shown in Figure 1c to be enhanced in 2005 and 2006 suggesting a role of temperature on the decline of ice maxima during these years. The elevated temperatures in 1984, 1996 and 1999 are also correlated with low winter ice maximum. However, this was not the case in 1988 and 1990 illustrating the complexity of the Arctic climate system with these later cases possibly influenced by strong wind divergence effects. Trends in winter temperatures over all sea ice and for regions > 70°N from 1981 to 2006 are 0.56 and 0.73 ^{o}C/decade, respectively, while the corresponding values with 2005 and 2006 excluded are 0.33 and 0.31 ^{o}C/decade. The temperature data also indicate progressively increasing average winter temperature from 1998 to 2006.

[7] Five-year means of daily values of extent and area over the summer period reported previously [*Comiso*, 2006] have been extended to include the winter period and 2006 data (Figure 2a). The five-year averages provide the means to assess how ice changed from one period to another and the plots indeed show downward decadal progression in the minimum extents from an average of 7.7 x 10^6 km^2 for the first two periods through 7.0 x 10^6 km^2 during the following decade to 6.5 x 10^6 km^2 for the period 2000 to 2004. In winter, it is apparent that the first three 5-year averages (i.e., from 1980 to 1994) are virtually overlapping at 15.8 x 10^6 km^2 while the following two (i.e., from 1995 to 2004) are also overlapping and only slightly reduced at 15.4 x 10^6 km^2. For comparison, the corresponding values for the individual years in 2005 (black) and in 2006 (gold) the maximum extents are 14.8 x 10^6 km^2 and 14.6 x 10^6 km^2, respectively, which are significantly lower than the averages for the previous years. Currently available ice data up to May 2006 also show that the 2006 extents are lower than those of 2005 suggesting that the perennial ice cover in 2006 might break the record low values in 2005. Similar 5-year average plots but using weekly surface temperatures over sea ice covered regions are shown in Figure 2b. The average surface temperatures of the ice cover during the winter periods of 2005 and 2006 are also shown and indeed they were significantly higher than normal indicating consistency with the observed decline in the winter ice cover. Also, the temperature record for 2005 show a rapid increase in May which means an early spring break-up that may have contributed to the low perennial ice for the same year. A similar rise in surface

temperatures in April and May of 2006 suggests that the sea ice cover in the summer of 2006 might resemble that of 2005.

3. Wind effects and anomalies in the ice cover and surface temperatures

[8] The geographical locations of the regions where negative ice anomalies are most prominent during the winters (January and February) of 2005 and 2006 are presented in Figure 3. It is apparent that the images show a dominance of negative ice anomalies (reds) which are prominent around the periphery of the Arctic sea ice cover in 2005 while in 2006, some positive anomalies in the western region are indicated but compensated by relatively extensive negative anomalies in the eastern (Barents Sea) region. The location of the negative anomalies in the eastern region is also adjacent to or within the perennial ice region, making the latter even more vulnerable to further decline.

[9] Average surface wind vectors (from NCEP) during the same months are superimposed on the ice anomaly maps to evaluate how wind might have affected the spatial distribution of the ice cover. Depending on strength and direction, wind affects the ice cover in many ways, such as causing the ice floes to break into smaller pieces and make them more vulnerable to melt, causing ice to drift to other regions including warmer water where they melt, or causing a compaction of the ice cover through rafting or ridging. It can also bring warm temperatures from the south and inhibit the surface water from freezing. In January 2005, two cyclonic patterns are apparent: one at $(50^oN, 178^oE)$ and the other at $(72^oN, 3^oE)$ both of which are adjacent to areas of high negative anomalies. Similar patterns are apparent in February 2005 with the increased anomaly likely influenced by an elevated wind intensity at the Sea of Okhotsk. In 2006, the patterns are very different with the big negative ice anomaly in the eastern side in January likely influenced by strong and warm winds from the Atlantic Ocean while the positive anomaly in the Bering Sea was likely caused in part by cold winds from the Central Arctic basin. In February 2006, the wind directions in the Bering Sea were almost opposite those in January and may have causedthe smaller positive anomaly (in the western side) and negative anomaly to the eastern side of the region. The wind directions were also reversed in the eastern/Barents Sea side (Figure 3d) and may have caused the reduction in the spatial extent of the negative ice anomaly. The wind patterns are coherent with the ice cover distribution but these patterns vary from one month to another and were not consistent during the winter months of 2005 and 2006. It is thus apparent that wind is a contributing but not the controlling factor that led to the anomalously low winter values in 2005 and 2006. It is evident from the southerly wind direction that the anomalously low extent (at least for the January 2006 period) in the eastern region is unlikely caused by the loss of a large fraction of ice drifting south through the Fram Strait. But wind may have caused the advection of perennial ice from the eastern region to the western region of the Arctic causing in part the loss of ice in the region.

[10] The corresponding clear-sky surface temperature anomalies for the same set of months are presented in Figure 4 and it is apparent that the spatial features are strongly correlated with corresponding features in the ice anomalies. Comparing Figures 3 and 4, areas of strong negative anomalies (purples and reds) in the ice cover are shown to be regions where strong positive anomalies (purples and reds) in surface temperatures are also apparent. Even the areas of positive ice anomalies (greens and blues) as in the Bering Sea in January 2006 (Figure 3) are shown to correspond to areas of negative surface temperature anomalies (greens and blues).

Regions where sea ice has retreated are normally shown as regions with positive temperature anomalies since liquid water is warmer than ice covered surfaces. However, the temperature anomalies are shown to extend far into the inner regions reflecting the more spatially extensive warming effects of the atmosphere.

[11] The temperature data represent the intensity of long wave (11.5 µm) radiation from the surface and therefore can be used to study the impact of greenhouse warming. Large positive anomalies especially in the Central Arctic are evident indicating the continuation of a pattern of warming in the 2000s and 1990s compared to the 1980s (Comiso, 2006). Overall, however, the data are not easy to interpret since the location and size of the anomalous features change in time and positive anomalies in some regions occur concurrently with negative anomalies in other regions. For example, Figure 4c show unusually high positive surface temperature anomaly in the Central Arctic in January 2006 which may have been caused in part by unusually strong and warm winds from the south (Figure 3c) and the effect of cyclones moving to the north. During the same period, large areas of negative temperature anomalies are observed in Russia and also in the Bering Sea region, which is where sea ice is observed to have advanced. The annual temperature anomalies over the period from 1981 to the present have been studied, however, and results show a dominance and persistence of positive anomalies in the Arctic region in the last decade compared to previous years [*Comiso,* 2006]. The winter temperatures may be in the process of catching up with trends for the other seasons.

[12] The Arctic Oscillation (AO) indices have been used to characterize the overall state of the polar atmosphere [*Thompson and Wallace,* 1998] and to interpret interannual variations in the sea ice cover. In the 1980s and early 1990s, the sign and magnitude of AO indices have been associated with the strength of ice drift and the volume of the sea ice cover (Lindsay and Zhang, 2005). However, the indices have been on neutral for the last 9 years and the previous interpretation has been questioned in light of significant declines in the perennial ice cover during these years [*Overland and Wang*, 2005]. A regression analysis of winter AO indices with ice extent in winter and summer for the period from 1979 to 2006 yielded correlation coefficients of 0.22 and -0.27, respectively, while similar regression using surface temperature instead of ice extents yielded correlation coefficients of -0.10 and -0.23. The correlation of AO with these polar parameters are significant but relatively weak. The possible connection of the El Niño Southern Oscillations (ENSO) on the winter maxima and surface temperature was also studied and similar regression analysis using ENSO indices yielded correlation coefficients of less than 0.2 with and with no lag analysis applied.

[13] Despite the relatively weak correlation of ice and temperature parameters with AO and ENSO, the direct effect of atmospheric forcing is evident as illustrated in Figures 3 and 4. The impact of strong winds, including cyclones from the south and the presence of anomalously warm temperatures in the regions of decreasing ice cover apparently contributed to the anomalously low ice maximum extents in 2005 and 2006. Because of the complexity of the Arctic climate system, it is not easy to sort out why wind was anomalously strong and why the temperatures were anomalously warm during the period. The strongly coupling of the various variables also need to be considered. For example, strong winds would cause the breakup of ice and the formation of new ice which in turn would cause enhanced surface temperature and increases in longwave radiation to the atmosphere. Is the warmer temperature in part caused by

ice-albedo feedback? With the perennial ice cover declining, more solar energy is being absorbed by the surface and hence warmer surface temperatures are expected. The effect of ice-albedo feedback would be most prominent in the Arctic basin in summer during the peak of solar insolation.   In the western/Beaufort Sea region where perennial ice retreated considerably from 1998 to 2004, sea ice has recovered in 2005 and therefore the effect of ice-albedo feedback in the region is not so apparent. Advection of perennial ice from east to west can explain in part the ice recovery in the west.   But overall, the expected changes in wind circulation from anticyclonic to cyclonic (and vice versa) are not so evident from results of analysis of monthly wind data before (not shown) and during the study period. Possible increase in the frequency of cyclones that contributes to strong winds and the advection of moist and warm air masses from the south can be a factor but such information are generally not known. More in depth analysis is required to determine the definite causes of the ice retreat and anomalously warm temperatures in the winters of 2005 and 2006 and also to assess the associated impact of greenhouse gases but such study is not within the scope of this paper.

4. Discussion and Conclusions

 [14] Overall, the maximum ice extent and area of sea ice in the Arctic have been relatively stable until 2005 and 2006 when the values were about 6% lower than average for each year. This phenomenon, which is correlated with surface temperature, is occurring in peripheral seas but primarily in the eastern part of the Arctic basin near the North Pole, where the perennial ice cover, which has been declining rapidly, becomes even more vulnerable. The ice anomaly in the eastern region is in part caused by wind-induced advection of the perennial ice to the western region. Significant delay in the onset of freeze-up appears to be reflected in the winter ice data of 2005 and 2006 in part because of abnormally warm temperatures. Recent reports of increasing length of the melt period (of 15 days per decade) over the sea ice region [e.g., *Comiso,* 2006; *Belchansky* et al., 2004] means a shortening of the growth period that will likely cause a continuation in the decline of the extent of the winter ice maxima in the near future.

 [15] The distribution of clear-sky surface temperatures in the Central Arctic in 2005 and 2006 exhibits a pattern of warming in winter that may in part reflect the warming effect of increasing atmospheric greenhouse gases. Progressively increasing surface temperatures in the Arctic basin in winter since 1998 suggests that the impact of long wave radiation during winter months is becoming more apparent. Ice-albedo feedback effects and increasing atmospheric greenhouse gases would serve to accelerate the warming and also the downward trend in the winter ice cover. The abnormally low winter ice maximum extent and area and enhanced surface temperatures in 2005 and 2006, as reported in this paper, may just be the beginning of these trends which have been more apparent in other seasons. The decade of change, suggested by *Serreze and Francis* [2006] may have actually arrived.

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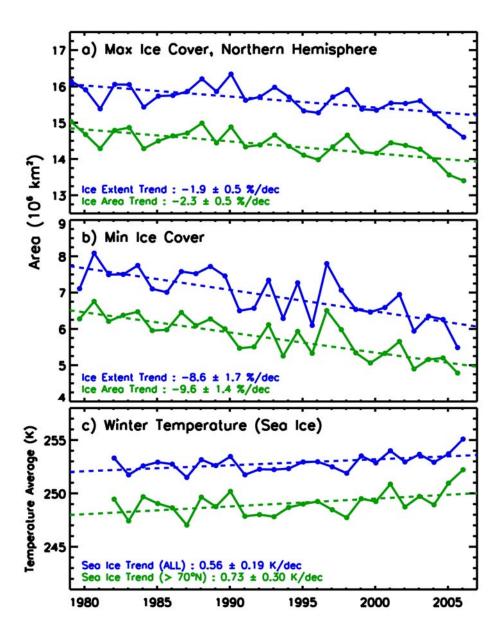
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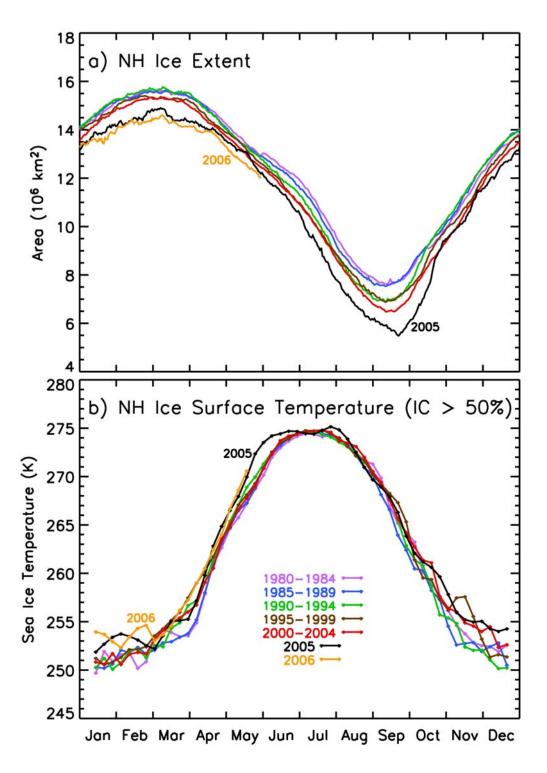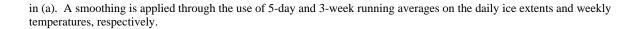

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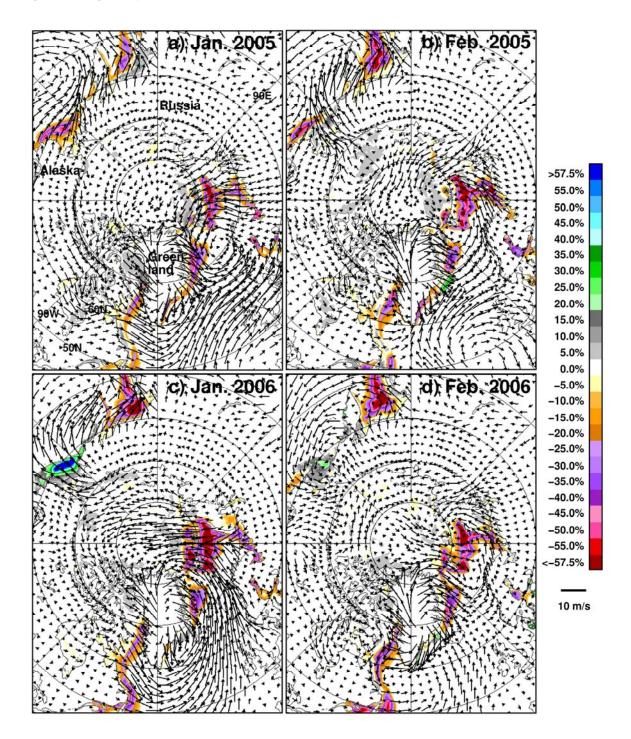
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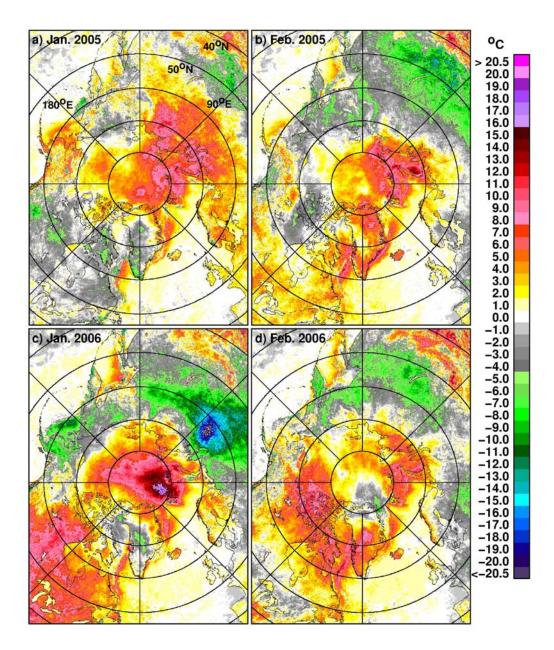
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