Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum

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[1] September 2007 marked a record minimum in sea ice extent. While there have been many studies published recently describing the minimum and its causes, little is known about how the ice thickness has changed in the run up to, and following, the summer of 2007. Using satellite radar altimetry data, covering the Arctic Ocean up to 81.5° North, we show that the average winter sea ice thickness anomaly, after the melt season of 2007, was 0.26 m below the 2002/2003 to 2007/2008 average. More strikingly, the Western Arctic anomaly was 0.49 m below the six-year mean in the winter of 2007/2008. These results show no evidence of short-term preconditioning through ice thinning between 2002 and 2007 but show that, after the record minimum ice extent in 2007, the average ice thickness was reduced, particularly in the Western Arctic. **Citation:** Giles, K. A., S. W. Laxon, and A. L. Ridout (2008), Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum, *Geophys. Res. Lett.*, *35*, L22502, doi:10.1029/2008GL035710.

1. Introduction

[2] September 2007 marked a record minimum in Arctic sea ice extent, 24% lower than the previous record low in September 2005, and 37% below the climatological mean [*Comiso et al.*, 2008; *Stroeve et al.*, 2008]. The downward trend in the September 1953 to 2006 Arctic sea ice extent has already been shown to be larger than any of the Intergovernmental Panel of Climate Change model predictions [*Stroeve et al.*, 2007], and the 2007 minimum has prompted speculation that the Arctic Ocean may become ice-free in the summer as early as 2013 [*Schiermeier*, 2008]. However, the question remains as to whether the events of 2007 were due to specific conditions occurring during that summer, or if summer 2007 marks a shift towards plummeting ice extents in subsequent years, or both.

[3] Since September 2007 a number of possible explanations have been suggested for the 2007 decrease in ice extent. *Kay et al.* [2008] associated reduced cloudiness and increased downwelling shortwave radiation over the Western Arctic (negative anomalies in ice extent occurred mostly in the Pacific sector of the Arctic) with the 2007 ice extent minimum. However, *Schweiger et al.* [2008] argued that results from their ice-ocean model suggest that these phenomena would not cause the observed decrease in ice extent in the Western Arctic. *Kwok* [2008] used passive microwave data to show a net transport of sea ice from the Pacific sector to the Atlantic sector of the Arctic, explaining 15% of the total area of retreat in 2007. In addition, his results suggested a significant convergence of ice onto the coasts of North Greenland and Ellesmere Island. *Perovich et al.* [2008] showed enhanced bottom melt of ice in the Beaufort Sea using data from an ice mass balance buoy (IMB). Their calculations indicated that increased solar heating of the upper ocean, caused by an increase in the open water fraction, which triggered a positive ice-albedo feedback, could account for the ice melt. Using a model *Zhang et al.* [2008a] showed the combined effect of a strengthened transpolar drift of sea ice and increased solar heating, due to an abnormally high open water fraction caused by the advection of sea ice from the region, caused the 2007 ice extent minimum. *Kay et al.* [2008], *Zhang et al.* [2008a] and *Comiso et al.* [2008] all suggest that preconditioning of the ice, due to the thinning of multi-year sea ice, or the replacement of multi-year ice by first-year ice, in previous years, is also a likely contributor to the 2007 minimum.

[4] Recent publications have also focused on the state of the Arctic sea ice following the 2007 September minimum. *Zhang et al.* [2008b] used ensemble predictions to predict a substantial reduction in ice thickness in Spring and Summer 2008, with up to 1.2 m thinning in the Canada Basin. However, despite a thinner ice cover in 2008, they do not predict that the summer minimum ice extent in 2008 will be dramatically lower than that of 2007. *Haas et al.* [2008] used helicopter-borne electromagnetic sea ice measurements to show that the mean ice thickness (excluding open water) around the North Pole in the late summer of 2007 was 1.01 m lower than in 2001 and 1.33 m lower than in 2004.

[5] Model studies have suggested that ice thickness and ice extent are intrinsically linked [*Lindsay and Zhang*, 2005]. Observations of ice age have suggested that the loss of the oldest and thickest ice between March 1982 and March 2007 contributed to the 2007 ice extent minimum [*Maslanik et al.*, 2007]. *Kwok* [2007] also showed that extensive melt over the summer of 2005 resulted in near zero replenishment of multi-year ice at the beginning of the following winter, presumably reducing the basin-wide average ice thickness. To understand the causes of the dramatic change in ice extent in 2007, we need to understand how the ice thickness has changed. In this paper we present the first, circumpolar estimates of Arctic sea ice thickness change in the run up to, and since, the record 2007 September ice extent minimum. We use satellite radar altimetry data to determine anomalies in sea ice thickness, in both time and space, over the five winter seasons (October 2002/March 2003 to October 2006/March 2007)

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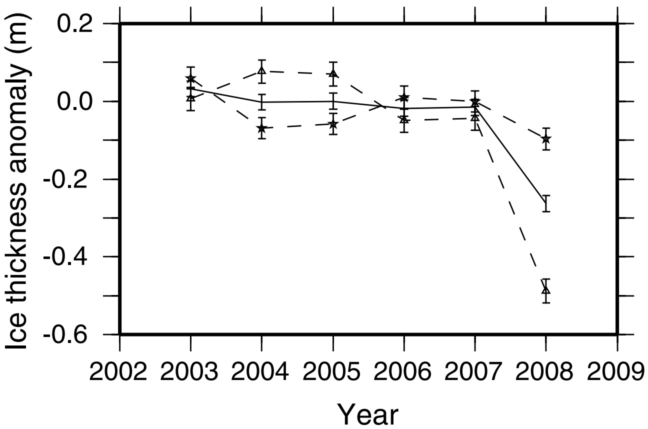

Figure 1. Circumpolar (solid line), Western Arctic (dashed line with triangle), and Eastern Arctic (dashed line with star), average winter season (October to March) ice thickness anomalies. Errors on the average anomalies, from variations in the snow loading, density uncertainties and measurement noise, are computed from the errors on the gridded anomalies. The circumpolar average includes all the data points shown in Figure 2. The locations of the Eastern and Western Arctic areas are shown in Figure 2. The data have been seasonally adjusted to 1st of January and only data points where there are coincident data in all years have been included in the average.

leading up to the 2007 ice extent minimum, and in the following winter (October 2007/March 2008).

2. Data and Methodology

[6] Sea ice thickness anomalies from satellite radar altimeter data were first obtained by *Laxon et al.* [2003] using data from European Space Agency (ESA) satellites ERS-1 and ERS-2. The satellite radar altimetry data used in this study were taken from the ESA satellite Envisat between the winter season 2002/2003 (October to March) and the winter season 2007/2008. The RA-2 altimeter on Envisat includes a Ku-band, pulse-limited altimeter, similar to that employed on the earlier ERS satellites. These satellites have a latitudinal limit of 81.5° N and cover most of the first-year ice and more than half of the multi-year ice. We use a similar method to *Laxon et al.* [2003] to calculate sea ice thickness from measurements of ice freeboard (we define ice freeboard as the level of the snow/ice interface above the ocean), with a small additional correction for the radar travel time through the snow pack [*Richardson et al.*, 1997]. This method excludes open water and ice less than 0.5 m thick from our estimates, but this has a marginal effect on our results [*Laxon et al.*, 2003]. The technique involves measuring the sea ice freeboard height and the sea surface height [*Peacock and Laxon*, 2004] above a reference surface. Discrimination between the open water and newly frozen leads and ice floes is achieved by analyzing the return echo shape [*Peacock and Laxon*, 2004]. Ice freeboard is then calculated by subtracting the sea surface height from the ice freeboard height and is then converted to ice thickness by assuming hydrostatic equilibrium and using values of 915.1 kg m^{-3} and 1023.8 kg m^{-3} for the ice and water densities respectively [*Wadhams et al.*, 1992], and a snow depth and density climatology from *Warren et al.* [1999].

[7] To generate winter averages for each season, the data were seasonally adjusted to the 1st January using an average winter growth curve derived from the data. The seasonally adjusted data were averaged onto 100 × 100 km grid cells on a polar stereographic projection. We estimated the errors in ice thickness for each grid cell as follows: The error in the ice freeboard was calculated using equation (1) from *Giles and Hvidegaard* [2006], with an additional term to account for the error in the velocity of the radar signal through the snow pack. The error in the estimate of ice thickness in each grid cell was then calculated from equation (3) of *Giles et al.* [2007], with errors in the ice and water densities taken to be 5 kg m^{-3} and 0.5 kg m^{-3} respectively [*Wadhams et al.*, 1992], the snow density error taken to be 3 kg m^{-3} [*Warren et al.*, 1999], and snow depth error taken to be the interannual variability (IAV) in snow depth of 0.03 m from *Radionov et al.* [1996]. For each winter season we then calculated ice thickness anomalies for each grid cell, which contained data for all years, by removing the six-year mean thickness for that cell. The error in the anomaly for each grid cell was also computed. Our grids of ice thickness anomalies were then averaged over the Arctic for each winter season, inversely weighted by the error on each grid cell, to generate regional or circumpolar averages. We have chosen to exclude the Fram Strait from these averages as the ice thickness there depends mainly on advection.

3. Results and Discussion

[8] Our results show that during the winter season 2007/2008, after the record September minimum ice extent, the circumpolar, average ice thickness was 0.26 m below the average winter-season ice thickness over the previous 6 years (Figure 1). Winter seasons 2002/2003 to 2006/2007 show a remarkably constant average ice thickness anomaly compared to *Laxon et al.* [2003], indicating little change in the circumpolar, average sea ice thickness in the Arctic Ocean during those years. The correlation between the sea ice freeboard anomalies for the three winter seasons of overlap (2002/2003 to 2004/2005) of Envisat and ERS-2, which has been validated by submarine estimates of ice thickness [*Laxon et al.*, 2003], is 0.999. The ERS-2 data has not been included in this study as its coverage of the Arctic is spatially limited between 2002 and 2005, due to a failure of the satellite's on-board tape recorders. When considering satellite derived estimates of ice thickness, one must also consider the IAV in the snow loading, which can contribute to the annual change in ice freeboard. For example, in years of high snow load the ice freeboard is suppressed, resulting in a reduction in ice freeboard, and hence satellite derived ice thickness, even if the real ice thickness has remained constant. However, it would require positive changes in snow depth to be perfectly compensated by positive changes in ice thickness to produce the relatively constant ice thickness anomalies between the winters 2002/2003 and 2006/2007. For example, we would need years of thick ice to correspond to years of increased snow cover, which seems unlikely given that snow has an insulating effect on the ice and reduces the bottom freezing rate [*Warren et al.*,

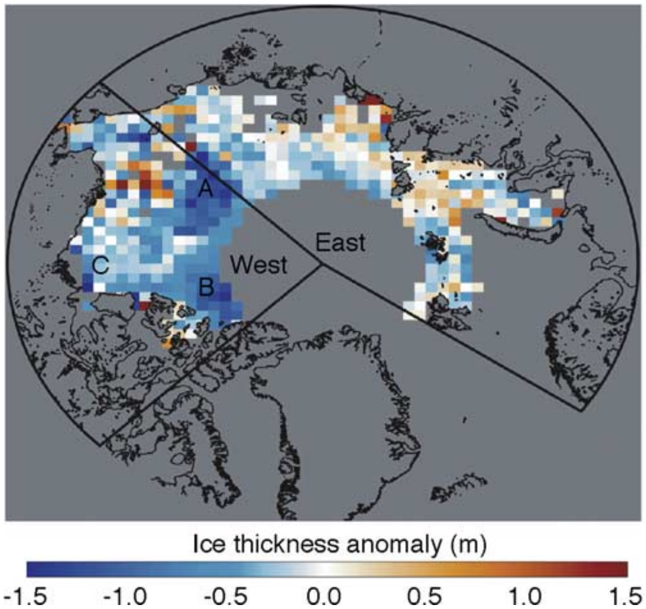

Figure 2. Map of the sea ice thickness anomaly for 2007/2008 (2007/2008 thickness minus the average thickness for 2002/2008). Anomalies greater or less than ± 1.5 m have been capped at ± 1.5 m. The grey areas are where there are no available data within our two regions. The location of the East and West Arctic areas are marked on the map, and A marks the North Chukchi Plateau, B marks the Canada Basin and C marks the Beaufort Sea.

1999]. The reduction in ice thickness (Figure 1) is consistent with preliminary results using Satellite Laser Altimetry from R. Kwok, shown on the National Snow and Ice Data Centre (NSIDC) website, which suggest that in spring 2008 the multi-year ice was thinner than in 2007 by 0.5 m, and the first year ice was thinner by 0.2 m (http://nsidc.org/arcticseaicenews/2008/071708.html).

[9] In the Western Arctic (Figure 1) a more variable picture emerges, with positive ice thickness anomalies in the 2002/2003 to 2004/2005 winter seasons followed by negative anomalies in 2005/2006 to 2007/2008. After the 2007 melt season the ice in the Western Arctic is, on average, 0.49 m thinner than the six-year mean. The second largest negative anomaly of −0.05 m occurs after the previous record summer ice extent minimum in September 2005. In the Eastern Arctic (Figure 1), the anomaly oscillates between positive and negative values with a maximum of 0.06 m in 2002/2003 and a minimum of −0.10 m in winter 2007/2008. The ice thickness anomalies in the Western and Eastern Arctic mirror one another until 2007/2008, when we see a decrease in thickness in both regions.

[10] Figure 1 shows that short-term preconditioning of the sea ice due to a reduction in ice thickness during the five previous winters, at least in areas up to 81.5° N, does not appear to be a major contributor to the record ice extent minimum in 2007. Instead our results imply that the low summer ice extents in 2007 and 2005 lead to a decrease in the ice thickness anomaly in the following winter season, particularly in the Western Arctic.

[11] The spatial distribution of the thickness anomaly for the winter season 2007/2008 (Figure 2) shows that the largest negative anomaly occurs over the north Chukchi Plateau (an average of −0.89 m), and the Canada Basin and Beaufort Sea also have large negative anomalies (averages of −0.63 and −0.36 m respectively). In the rest of the Arctic Ocean there are relatively small positive ice thickness anomalies around the coastal regions and in part of the Chukchi Sea. *Zhang et al.* [2008b] used ensemble predictions to estimate the largest reduction in ice thickness, up to 1.2 m, in spring and summer of 2008 in the Canada Basin, which is comparable to the maximum anomaly in this area of −1.57 m from our satellite data (Note that the *Zhang et al.* [2008b] value was the 2008 ice thickness minus the 2001–2007 mean ice thickness).

[12] *Perovich et al.*'s [2008] IMB data showed that during the summer of 2007 an ice floe drifting in the Beaufort Sea underwent 2.1 m of bottom melt, two and a half times the amount of melt seen in 2006, which equates to 1.3 m of extra melt in 2007. Our ice thickness anomalies in the Beaufort Sea (Figure 2) compare well to this result from *Perovich et al.* [2008], with the ice thickness in some areas thinner in winter 2007/2008 by at least 1.5 m. The average ice thickness anomaly over the Beaufort Sea in winter 2007/2008 is −0.36 m, which is less than the enhanced thinning in 2007 shown by *Perovich et al.* [2008].

4. Conclusions

[13] Our data show that during the winter season 2007/2008, after the record minimum sea ice extent in September 2007, the average Arctic sea ice thickness (below 81.5° N) was reduced by 0.26 m compared to the average ice thickness over the six winter seasons. The largest changes in sea ice thickness occurred in the Western Arctic where the average thickness anomaly was −0.49 m with the North Chukchi Plateau showing the largest regional negative ice anomaly of −0.89 m. If the percentage of thin ice and open water (which our measurements exclude) was substantially higher in the winter of 2007/2008 these estimates represent a lower limit on the change in thickness. Our results show no evidence of short-term preconditioning below 81.5°N due to ice thinning in the winters immediately preceding either the 2007 or the 2005 minimum. Instead, following the 2007 and 2005 ice extent minima, the average ice thickness was reduced, particularly in the Western Arctic. The reduction in ice thickness in winter 2007/2008 could be due to a number of factors: Firstly, a reduction in the quantity of first year ice left at the end of the melt season reduces the amount of second year ice. *Kwok* [2007] shows near zero replenishment of multi-year ice at the end of summer 2005, after which we see the second largest negative ice thickness anomaly in the Western Arctic. (It would be interesting to extend his time series to include data from 2006 and 2007 to investigate whether there was also near zero replenishment of multi-year ice at the end of summer 2007.) Secondly, a greater exposure of the ocean during the summer, leading to increased solar heat input would inhibit ice growth during the following winter [*Perovich et al.*, 2008].

[14] On a regional basis we see thinning over a wide area of the Arctic, particularly in the Western Arctic, over the North Chukchi Plateau and in the Canada Basin and Beaufort Sea. The 2008 September sea ice extent is the second lowest after the record September 2007 minimum.

Although the same anomalous atmospheric conditions did not occur during the summer of 2008, the ice extent dropped to within 10% of the 2007 minimum (http://nsidc.org/arcticseaicenews/2008/091608.html). It is possible that the thinner ice cover that we observe in the winter of 2007/2008 meant that the ice was preconditioned for melt during the summer of 2008. However, more detailed studies, including the analysis of thermodynamic and dynamic forcing, would be needed to confirm this idea.

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