GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 1356–1361, doi:10.1002/grl.50349, 2013

On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm

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Received 7 January 2013; revised 5 March 2013; accepted 8 March 2013; published 12 April 2013.

[1] A new record low Arctic sea ice extent for the satellite era, 3.4×10^6 km^2, was reached on 13 September 2012; and a new record low sea ice area, 3.0×10^6 km^2, was reached on the same date. Preconditioning through decades of overall ice reductions made the ice pack more vulnerable to a strong storm that entered the central Arctic in early August 2012. The storm caused the separation of an expanse of 0.4×10^6 km^2 of ice that melted in total, while its removal left the main pack more exposed to wind and waves, facilitating the main pack's further decay. Future summer storms could lead to a further acceleration of the decline in the Arctic sea ice cover and should be carefully monitored. **Citation:** Parkinson, C. L., and J. C. Comiso (2013), On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm, *Geophys. Res. Lett.*, *40*, 1356–1361, doi:10.1002/grl.50349.

1. Introduction

[2] On 13 September 2012, Arctic sea ice coverage decreased to its lowest areal expanse since the start of the satellite multichannel passive-microwave record in November 1978, reaching new record minima in both ice extent (ocean area with ice concentration of at least 15%) and ice area (cumulative area of actual ice coverage). Ice extent and area both descended to well below the previous record minima established in 2007, even though in 2007 the ice had plummeted to under 76% of the ice extent in any previous year in the satellite record [see *Comiso et al.*, 2008; *Lindsay et al.*, 2009].

[3] Arctic sea ice has an important place in climate change discussions both because of being an indicator of climate change and because changes in the ice cover feed back to impact other components of the climate system. Most notably, as the Arctic ice cover retreats under warming conditions, some of the solar radiation that the ice would have reflected back to space instead becomes absorbed in the ocean, staying within the Earth system and contributing to further warming, providing a classic positive feedback [e.g., *Kellogg*, 1975] and contributing substantially to north polar amplification of climate change [*Screen and Simmonds*, 2010]. It thus becomes of interest to consider what might have contributed to the record decline of the Arctic ice cover in 2012.

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0094-8276/13/10.1002/grl.50349

2. Preconditioning: Arctic Sea Ice Decreases Prior to 2012

[4] Warming of the Arctic in recent decades has been well documented [see *Comiso*, 2006; *Comiso and Parkinson*, 2004; *Hansen et al.*, 2010], and among the consequences of this warming (and a factor in it) has been a decreasing Arctic sea ice cover [e.g., *Lindsay and Zhang*, 2005], which now also is well documented through satellite imagery.

[5] Satellite multichannel passive-microwave data provide a record of Arctic sea ice area, extent, and concentration since late 1978. For this study, we use data from the National Aeronautics and Space Administration (NASA) Scanning Multichannel Microwave Radiometer (SMMR), which operated from late October 1978 to mid-August 1987, and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) and SSMI Sounder (SSMIS), which have operated from July 1987 to the present. The ice concentration data were derived using the Bootstrap Algorithm, which provides results similar to those derived using the NASA Team 2 (NT2) algorithm [*Comiso and Parkinson*, 2008]. The ice concentrations are mapped at 25 km resolution. The daily ice concentration fields can be obtained from the National Snow and Ice Data Center (NSIDC) at nsidc.org, generally with a delay of no more than a few days for the near-real-time product and on the order of 1 year for the quality-controlled product.

[6] The 1979–1986, SMMR record showed a slight decrease in the areal extent of Arctic sea ice [*Parkinson and Cavalieri*, 1989], but the decrease became far stronger and more convincing with the addition of the first decade of the SSMI data [*Parkinson et al.*, 1999] and has continued to strengthen in the subsequent 16 years [e.g., *Meier et al.*, 2007; *Cavalieri and Parkinson*, 2012; *Stroeve et al.*, 2012]. When the daily ice extents and areas are averaged to yearly averages and trends are calculated, the trends in yearly averaged Arctic sea ice extents and areas over the 32 year period 1979–2010 are $-51.5 \pm 4.1 \times 10^3$ km^2/yr (-4.1 ± 0.3%/decade) and $-49.6 \pm 4.0 \times 10^3$ km^2/yr (-4.6 ± 0.4%/decade), respectively. On a daily basis, both extents and areas reached then-record minima in September 2007 and rebounded partially in the next 3 years [*Cavalieri and Parkinson*, 2012].

[7] The areal decline in perennial ice (ice that has survived at least one summer melt season) and multiyear ice (variously defined, but used here as ice that has survived at least two summer melt seasons) is even greater percentage-wise than the decline in the total ice cover [*Nghiem et al.*, 2007; *Comiso*, 2012]. Specifically, over the 1979–2010 period, the extent and area of the perennial ice declined by 12.2%/decade and 13.5%/decade, respectively [*Comiso*, 2012]; when updated to 2012, the extent and area rates of decline rise to 14.1%/decade and 15.8%/decade, respectively. The extent and area of the

multiyear ice declined by even more, at 17.1%/decade and 19.1%/decade, respectively, for the period 1979–2012. (“Extent” of perennial ice is the ocean area with perennial ice concentration of at least 15%, although, to avoid issues with second-year ice, “extent” of multiyear ice is the ocean area with multiyear ice concentration of at least 30%, as explained in *Comiso* [2012].) The perennial and especially the multiyear ice constitute the thick component of the Arctic ice cover and hence are the ice types most likely to survive the summer melt season, if not advected into warmer waters.

[8] The areal retreat of the Arctic ice pack, determined from satellite data since late 1978, has occurred in conjunction with a thinning of the ice, determined largely from submarine measurements since the 1950s [e.g., *Yu et al*., 2004], augmented in the early 21st century by a much shorter record from satellite laser altimetry [*Kwok and Rothrock*, 2009]. The submarine record is scattered in both time and space, being limited to where and when submarines were operating; and although the satellite laser altimeter record has much better spatial coverage, it is limited greatly in time, being available only for select periods between January 2003 and August 2010. Still, despite the limitations, *Kwok and Rothrock* [2009] were able to conclude that the average wintertime ice thickness in the submarine data release area (covering ~38% of the Arctic Ocean) decreased from about 3.64 m in 1980 to about 1.89 m in 2008. This indicates an ice thickness decrease of 48% over the 1980–2008 period, for an average thinning of 17.1%/decade, matching the %/decade decrease of the extent of multiyear ice.

[9] An additional change brought about by warming that has further weakened the Arctic ice cover is increased puddling (or meltponding) on the ice. With warming, a greater proportion of Arctic precipitation now falls as rain, resulting in increased puddling, which lowers the ice albedo and increases the absorption of solar radiation [*Screen and Simmonds*, 2012]. The increased radiation absorption provides energy for further decay within the ice floes. (Puddling also influences the microwave signature of the ice, as the puddles contribute a liquid-water signal. This affects the derived ice concentrations during periods of puddling. However, these complications to the satellite-based derivations have limited if any effect on the perennial and multiyear ice trends, because perennial ice is determined from September conditions and multiyear ice from winter conditions. During the period of our study, puddling is not likely in either September or winter.)

[10] The combination of the significant reduction in areal ice coverage (which decreases the albedo, thereby increasing solar radiation absorption), the significant thinning of the ice (which increases the open water formation for any specific melt rate [*Holland et al*., 2006]), and the further weakening of the ice through such processes as increased puddling (*Screen and Simmonds* [2012]) left the remaining Arctic ice cover in 2012 more vulnerable to the storm that arrived in the central Arctic in August 2012 than it would have been in earlier decades.

3. Surface and Atmospheric Conditions in the Arctic in Summer 2012

3.1. Sea Ice Conditions and Pre-August Storm Conditions

[11] Considering the full 1979–2012 satellite record, daily sea ice extents and areas (or “ice coverage”) in autumn 2011 were relatively low, comparable to the values in 2007 through much of the season after mid-October (Figure 1a). However, the subsequent wintertime expansion of the Arctic ice was greater than usual, with the result that in late March, April, and May 2012, the ice coverage was comparable to that in the decade 1989–1998. A major change, relative to previous years, occurred in early June 2012, during the late-spring ice retreat, as the ice coverage decreased faster than normal, reaching the level of the 2007 and 2011 conditions (decidedly below the averages for 1979–2008) by mid-June (Figure 1a). Ice coverage then remained comparable to that in 2007 and 2011 from mid-June until early August 2012. In August 2012, the ice decline accelerated again, proceeding at a faster rate than in previous years and sending the ice coverage below the 2007 and 2011 levels for the same dates. In fact, by 20 August 2012, the ice area had dropped below the previous record minimum ice area,

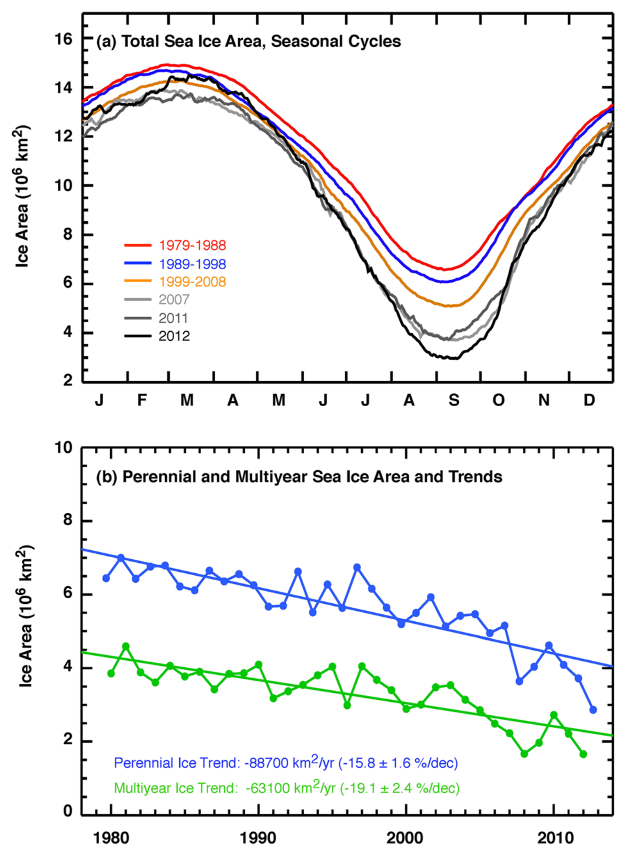

Figure 1. (a) Seasonal cycles of daily Arctic sea ice area for the decades 1979–1988, 1989–1998, and 1999–2008, and the individual years 2007 (which included the record minimum prior to 2012), 2011, and 2012. The curves for sea ice extent (not shown) are quite similar, although shifted upward by about 0.5–1.0 × 10^6 km^2. (b) Perennial ice areas for 1979–2012, plotted at the date of minimum ice coverage for each year, generally in September, and multiyear ice areas for 1980–2012, averaged for December, January, and February and plotted at January of each year. Tick marks on the *x*-axis are placed at the start of the year. The corresponding plots for the multiyear and perennial ice extents are similar and have the following trends: $-89{,}800$ km^2/yr (-14.1 ± 1.6%/decade) for perennial ice and $-82{,}000$ km^2/yr (-17.1 ± 2.0%/decade) for multiyear ice.

3.6×10^6 km^2 reached on 14 September 2007 [*Comiso et al.*, 2008], and by 26 August 2012, the ice extent had dropped below the previous record minimum ice extent, 4.1×10^6 km^2, also reached on 14 September 2007 [*Comiso et al.*, 2008] (Figure 1a). The 2012 ice cover continued to decrease, although largely at a reduced rate, until 13 September 2012, on which date it reached its new record minima of 3.4×10^6 km^2 for ice extent and 3.0×10^6 km^2 for ice area (Figure 1a). The time series of ice coverage therefore identify two crucial periods in the run-up to the record sea ice minima: early June and early August.

[12] Examination of wind fields from National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data [*Kalnay et al.*, 1996; *Saha et al.*, 2010] reveals no major storms in the Arctic in June 2012 (see www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html). Storms are consequently rejected as the primary cause of the unusual June decay of the ice cover. Minor storms in the Bering Sea region in the first week of June and in the Kara Sea region the following week are visible in the reanalysis data and likely had some impact on the ice. However, the greater impact was probably the state of the ice cover itself. Perennial ice in 2011 was close to as low as that in 2007, and multiyear ice in the 2011–2012 winter season was a record low (Figure 1b). This, along with the unusually large ice area increase in February and March 2012, suggests that the greater ice area in March 2012 than in March 2007 (Figure 1a) was largely from a greater expanse of seasonal ice. The more expansive seasonal ice would contribute to a larger ice decay in June 2012 than in June 2007, other factors being equal, as seasonal ice—especially late-forming seasonal ice, as in February and March 2012—tends to be thinner and more vulnerable than multiyear or perennial ice.

[13] The lack of a specific weather event to connect to the June 2012 ice retreat is in sharp contrast to what occurred in August 2012, when weather conditions included a storm well timed and situated for a case study on the impact that an individual storm can have on the Arctic ice.

3.2. August 2012 Storm

[14] A major storm moved into the central Arctic from Siberia in early August 2012. By 6 August 2012, this storm (then centered at approximately 81ºN and 165ºW) overlaid a substantial portion of the Arctic Ocean and was shearing off from the main Arctic ice pack a sizeable, 0.4×10^6 km^2 area of ice to the north of the Bering Strait (Figure 2). The storm reached its peak intensity on 6–8 August and by 10 August had died down and moved further to the east. In the meantime, a second, lesser storm had emerged on the other side of the Arctic, centered at approximately 77ºN and 80ºE (Figure 2).

[15] The major August 2012 storm is described in detail by *Simmonds and Rudeva* [2012], who labeled it "The Great Arctic Cyclone of August 2012" and provided the following relevant details and conclusions: It reached its lowest central

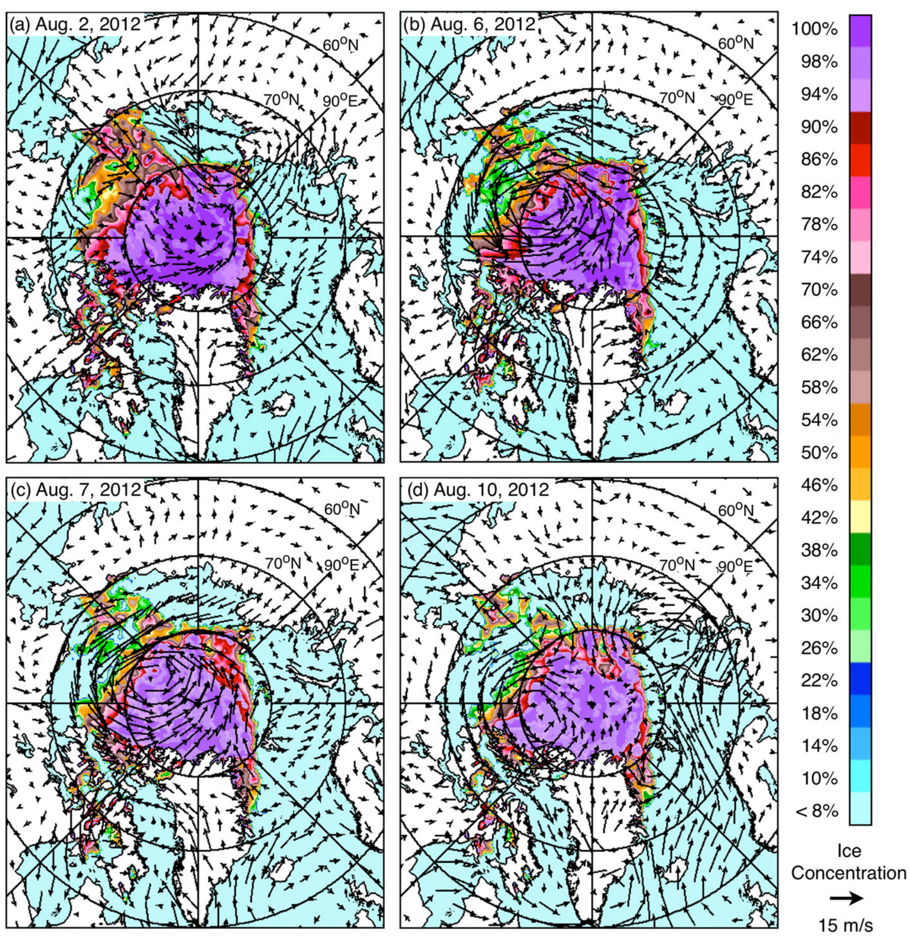

Figure 2. Maps of sea ice concentration from the SSMIS, overlain by wind vectors from NCEP, 2–10 August 2012.

pressure of 966 hPa on 6 August; it lasted for almost 13 days; it is unlikely that sensible and latent heat fluxes from the ocean or sea ice concentrations played a significant role in the storm's progress; its evolution instead was strongly influenced by the tropopause polar vortex; and it likely contributed to the unusually large August sea ice reductions.

[16] Not only did the major August 2012 storm facilitate the melt of sea ice by bringing to the Arctic heat and moisture from the south, but by shearing off a sizeable segment of the ice (approximately 0.4×10^6 km^2), it further led to an accelerated ice-cover decay. The sheared-off portion was in the Bering Strait/Chukchi Sea vicinity, where further fracturing and melting of the ice was facilitated by greater exposure to liquid water and the wave action induced by the storm. This led to a swift decay of the ice in the sheared-off portion (Figure 2). Further, by losing the buffering of the sheared off ice, the remaining ice pack in the vicinity was subject to enhanced decay as well, as it was now adjacent to open ocean, which was absorbing solar radiation (providing energy for ice melt) that in the presence of the ice would have been reflected back to space.

3.3. Additional Possible Influences

[17] The decreasing areal coverage of ice in the Arctic Ocean in recent decades (section 3.1) has allowed the absorption of more solar radiation and hence more warming of the ocean surface. The occurrence of such warming has been reported by *Steele et al*. [2008], based on in situ measurements and satellite data, with warming particularly pronounced since 2000 and with summer 2007 sea surface temperature (SST) anomalies as high as 5 °C. Anomalously high 2007 SSTs were also reported by *Shibata et al*. [2010], using AMSR-E data, and by *Perovich et al*. [2008], who found an unusually large amount of melting on the underside of the ice in the Beaufort Sea during the summer 2007 melt season. These results suggest that high

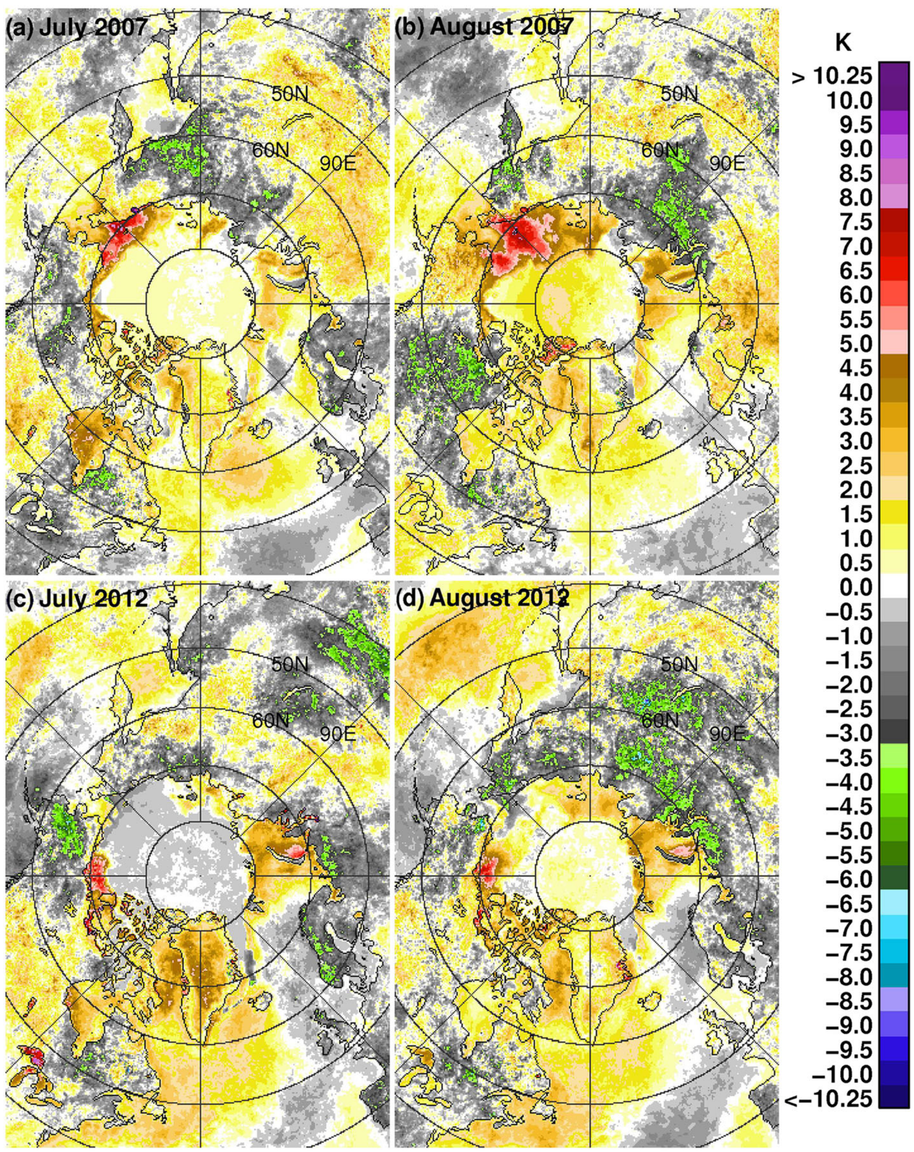

Figure 3. Monthly average surface temperature anomalies for: (a) July 2007, (b) August 2007, (c) July 2012, and (d) August 2012. Anomalies are calculated based on the July and August averages for 1981–2012. Temperatures are derived from thermal infrared data from a series of Advanced Very High Resolution Radiometers (AVHRRs) on satellites of the National Oceanic and Atmospheric Administration (NOAA).

SSTs might well have contributed to the then-record retreat of Arctic ice in 2007, along with persistent winds that pushed the ice away from the Siberian coast and toward northern Greenland and Ellesmere Island, leading to considerable open water in the eastern Arctic [e.g., *Comiso et al.*, 2008; *Kwok*, 2008 (see especially the August 2007 image in Figure 2 of the Kwok article); *Lindsay et al.*, 2009].

[18] A question of interest then becomes to what extent surface temperatures might have contributed to the new record low ice extents and areas in 2012. Figure 3 presents monthly anomaly maps of surface temperature for July and August of 2007 and 2012, relative to the corresponding averages for 1981–2012. These images confirm the likelihood that high surface temperatures might have been an important factor in the ice retreat in 2007, with high surface temperature anomalies apparent through much of the Arctic and in particular in the Chukchi Sea, western Beaufort Sea, and surroundings, where the ice retreat was anomalously large. This suggestion is supported by an extensive analysis done by *Graversen et al.* [2011] of anomalous input to the Arctic of warm, humid air from the Pacific that led to changes in surface fluxes sufficient to provide the energy to melt an additional 1 m of ice thickness during the melt season. In contrast, in 2012, negative temperature anomalies are apparent through much of this region in July and in a portion of the Chukchi Sea in August (Figure 3). Hence, surface temperature was likely not a major influence on the unusual retreat of the sea ice in 2012. In fact, very likely, there was the reverse impact, with the cold water melted from the sea ice in the Chukchi Sea region contributing to the anomalously cold temperatures. (The positive temperature anomalies in Baffin Bay and Hudson Bay in July and August 2012 [Figure 3] are irrelevant here because both bays are consistently ice-free at the end of summer.)

[19] Another potential influence on the 2012 ice cover is the Arctic Oscillation (AO). However, examination of the AO indices from 1979 onward does not suggest a strong impact of the AO on the record low ice coverages in either 2007 or 2012. In fact, correlation analyses of the AO with the multiyear ice area and multiyear ice extent yield considerable scatter and correlation coefficients of only -0.04 and -0.05, respectively. Lag analyses with sea ice lags of 1, 2, and 3 months behind the AO yielded no correlation coefficients higher in magnitude than 0.18. Relatedly, *Stroeve et al.* [2011] found that the extreme negative phase of the AO in the winter of 2009/2010 was not followed by a greater retention of Arctic ice in the 2010 summer, as some earlier studies of the AO had indicated it might be. The changing nature of the Arctic ice cover could be changing its responses to such atmospheric forcing as the AO [*Stroeve et al.*, 2011], contributing to its low overall correlation with the AO.

4. Discussion and Conclusions

[20] The sea ice cover in the Arctic at the end of summer 2012 was lower than it had ever been in the previous 33 years of satellite data. In fact, when compared also against a much longer record, incorporating pre-satellite data [*Walsh and Chapman*, 2001], it appears that the late-summer ice cover of 2012 is the lowest ice coverage in at least the past 112 years.

[21] With Arctic and global air temperatures on the rise over the past several decades [*Comiso*, 2006; *Hansen et al.*, 2010], it is not surprising that new record low sea ice extents occur with some frequency (most recently in 2005, 2007, and 2012). Each summer season has its own set of circumstances, and in 2012, the August 2012 storm was a factor of interest. Using daily ice data from satellite passive-microwave sensors and daily atmospheric data from satellite infrared sensors, we were able to monitor the impact of the August 2012 storm on the sea ice cover on a day-to-day basis, finding a high immediate impact of the storm on the sea ice cover. For example, in the southern region of the Chukchi Sea (specifically 68–76ºN and 164–205ºE), the ice area decreased by 30,000 km^2 (from 380,000 to 350,000 km^2) from 1–3 August, prior to the storm, but by 80,000 km^2 (from 310,000 to 230,000 km^2) from 5–7 August, during the storm.

[22] Wind patterns, although not a specific storm, were also important in 2007, when the Arctic sea ice area reached its previous record minimum [*Comiso et al.*, 2008; *Kwok*, 2008; *Lindsay et al.*, 2009]. More generally, *Simmonds and Keay* [2009] find a strong correlation between the increases in the strength and size of cyclones and decreases in September sea ice extent over the period 1979–2008, while *Screen et al.* [2011] find that low ice coverage at the end of the summer is favored by fewer rather than more cyclones earlier in the melt season, in May–July.

[23] The impact of the August 2012 storm on the sea ice decay during the storm does not mean that it was the only factor responsible for the decay or even that it was critical to the descent to a record minimum. The storm separated a 0.4×10^6 km^2 area of ice from the main ice pack, and, in a cryospheric version of "divide and conquer", this separated portion eventually melted entirely, accounting for 57% of the 0.7×10^6 km^2 difference between the 2007 and 2012 ice extent minima. Its removal also left the main pack depleted and hence more exposed to wind and waves, facilitating further decay. However, climate change also contributed to the 2012 record low, through preconditioning the ice pack, following decades of ice reductions, to be more vulnerable in 2012 than it would have been decades earlier (section 3.1). A storm of the same magnitude as the August 2012 storm likely would not have had a comparable impact decades ago, when the ice cover was much more substantial, being thicker [e.g., *Yu et al.*, 2004] and more expansive [e.g., *Cavalieri and Parkinson*, 2012; *Comiso*, 2012].

[24] It is quite likely that even without the storm, the Arctic ice cover might well have reached a new record minimum in 2012, in light of the preconditioning and the trajectory of the ice up until the time the storm occurred. In fact, *Zhang et al.* [2013] find just that result in a model sensitivity study. They simulate an unprecedented three-day ice volume loss during the three peak days of the storm (6–8 August 2012), but also simulate that a record minimum ice cover would have been reached even without the storm. Further, with a numerical model, they are able to examine variables that are not observed with the satellite data, and in doing so, they calculate that, at least in their model, the decrease in ice volume during the storm was in large part due to increased bottom melt caused by the wind-induced enhanced oceanic mixing, increasing the upward ocean heat flux.

[25] In a separate modeling study concerning an earlier Arctic storm, *Long and Perrie* [2012] simulate the reverse influence of the state of the sea ice cover on overlying storms. Using a coupled atmosphere-ice-ocean model, they simulate how the evolution of a 2008 Arctic summer storm

might have differed had the underlying sea ice cover not been as sparse as it was, nicely illustrating the important linkages among the ice, ocean, and atmosphere, linkages necessarily at play also in August 2012.

[26] The highly coupled nature of the ice-ocean-atmosphere system [*Long and Perrie*, 2012; *Zhang et al*., 2013], the high impact of the August 2012 storm on the August 2012 Arctic sea ice decline (section 3.2; Figure 2), and the upward trend in late-summer cyclone depths over the Arctic [*Simmonds et al*., 2008; *Simmonds and Keay*, 2009] together suggest that keeping track of Arctic cyclones in future summers might help elicit further insights into the rapidly declining Arctic ice and help resolve the puzzle of why many climate models have not predicted sea ice declines as fast as what the satellite observations reveal [*Stroeve et al*., 2007].

[27] **Acknowledgments.** The authors thank Rob Gersten of ADNET/RSIS and Larry Stock of SGT for their support in the creation of the figures and the Cryospheric Sciences Program at NASA Headquarters for funding the work. They also thank Ian Simmonds and Harry Stern for many valuable comments on the manuscript.

References

Cavalieri, D. J., and C. L. Parkinson (2012), Arctic sea ice variability and trends, 1979–2010, *The Cryosphere*, *6*, 881–889, doi:10.5194/tc-6-881-2012.

Comiso, J. C. (2006), Arctic warming signals from satellite observations, *Weather*, *61*(3), 70–76.

Comiso, J. C. (2012), Large decadal decline of the Arctic multiyear ice cover, *J. Climate*, *25*, 1176–1193.

Comiso, J. C., and C. L. Parkinson (2004), Satellite-observed changes in the Arctic, *Physics Today*, *57*(8), 38–44.

Comiso, J. C., and C. L. Parkinson (2008), Arctic sea ice parameters from AMSR-E data using two techniques and comparisons with sea ice from SSM/I, *J. Geophys. Res.*, *113*, C02S05, doi:10.1029/2007JC004255.

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock (2008), Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, *35*, L01703, doi:10.1029/2007GL031972.

Graversen, R. G., T. Mauritsen, S. Drijfhout, M. Tjernström, and S. Mårtensson (2011), Warm winds from the Pacific caused extensive Arctic sea-ice melt in summer 2007, *Clim. Dyn.*, *36*, 2103–2112.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Rev. Geophys.*, *48*, RG4004, doi:10.1029/2010RG000345.

Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, *33*, L23503, doi:10.1029/ 2006GL028024.

Kalnay, E., M. Kanamitsu, R. Kistler, and 19 others (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteorol. Soc.*, *77*(3), 437–471.

Kellogg, W. W. (1975), Climatic feedback mechanisms involving the polar regions, in Climate of the Arctic, edited by G. Weller and S. A. Bowling, pp. 111–116, University of Alaska, Fairbanks, Alaska.

Kwok, R. (2008), Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic sectors, *Geophys. Res. Lett.*, *35*, L03504, doi:10.1029/2007GL032692.

Kwok, R., and D. A. Rothrock (2009), Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, *Geophys. Res. Lett.*, *36*, L15501, doi:10.1029/2009GL039035.

Lindsay, R. W., and J. Zhang (2005), The thinning of Arctic sea ice, 1988–2003: Have we passed a tipping point?, *J. Climate*, *18*, 4879–4894.

Lindsay, R. W., J. Zhang, A. Schweiger, M. Steele, and H. Stern (2009), Arctic sea ice retreat in 2007 follows thinning trend, *J. Climate*, *22*, 165–176.

Long, Z., and W. Perrie (2012), Air-sea interactions during an Arctic storm, *J. Geophys. Res.*, *117*, D15103, doi:10.1029/2011JD016985.

Meier, W. N., J. Stroeve, and F. Fetterer (2007), Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record, *Ann. Glaciol.*, *46*, 428–434, doi:10.3189/172756407782871170.

Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colón, J. W. Weatherly, and G. Neumann (2007), Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, *34*, L19504, doi:10.1029/2007GL031138.

Parkinson, C. L., and D. J. Cavalieri (1989), Arctic sea ice 1973–1987: Seasonal, regional, and interannual variability, *J. Geophys. Res.*, *94*(C10), 14,499–14,523.

Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso (1999), Arctic sea ice extents, areas, and trends, 1978–1996, *J. Geophys. Res.*, *104*(C9), 20,837–20,856.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light (2008), Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, *Geophys. Res. Lett.*, *35*, L11501, doi:10.1029/2008GL034007.

Saha, S., S. Moorthi, H.-L. Pan, and 49 others (2010), The NCEP climate forecast system reanalysis, *Bull. Amer. Meteorol. Soc.*, *91*(8), 1015–1057, doi:10.1175/2010BAMS3001.1.

Screen, J. A., and I. Simmonds (2010), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, *464*, 1334–1337, doi:10.1380/nature09051.

Screen, J. A., and I. Simmonds (2012), Declining summer snowfall in the Arctic: Causes, impacts and feedbacks, *Clim. Dyn.*, *38*, 2243–2256, doi:10.1007/s00382-011-1105-2.

Screen, J. A., I. Simmonds, and K. Keay (2011), Dramatic interannual changes of perennial Arctic sea ice linked to abnormal summer storm activity, *J. Geophys. Res.*, *116*, D15105, doi:10.1029/2011JD015847.

Shibata, A., H. Murakami, and J. Comiso (2010), Anomalous warming in the Arctic Ocean in the summer of 2007, *J. Remote Sens. Soc. Japan*, *30*, 105–113.

Simmonds, I., and K. Keay (2009), Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008, *Geophys. Res. Lett.*, *36*, L19715, doi:10.1029/2009GL039810.

Simmonds, I., and I. Rudeva (2012), The great Arctic cyclone of August 2012, *Geophys. Res. Lett.*, *39*, L23709, doi:10.1029/2012GL054259.

Simmonds, I., C. Burke, and K. Keay (2008), Arctic climate change as manifest in cyclone behavior, *J. Climate*, *21*, 5777–5796, doi:10.1175/2008JCLI2366.1.

Steele, M., W. Ermold, and J. Zhang (2008), Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, *35*, L02614, doi:10.1029/2007GL031651.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Stroeve, J. C., J. Maslanik, M. C. Serreze, I. Rigor, W. Meier, and C. Fowler (2011), Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010, *Geophys. Res. Lett.*, *38*, L02502, doi:10.1029/2010GL045662.

Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Maslanik, and A. P. Barrett (2012), The Arctic's rapidly shrinking sea ice cover: A research synthesis, *Clim. Change*, *110*, 1005–1027, doi:10.1007/s10584-011-0101-1.

Walsh, J. E., and W. L. Chapman (2001), 20th century sea-ice variations from observational data, *Ann. Glaciol.*, *33*, 444–448.

Yu, Y., G. A. Maykut, and D. A. Rothrock (2004), Changes in the thickness distribution of Arctic sea ice between 1958–1970 and 1993–1997, *J. Geophys. Res.*, *109*, C08004, doi:10.1029/2003JC001982.

Zhang, J., R. Lindsay, A. Schweiger, and M. Steele (2013), The impact of an intense summer cyclone on 2012 Arctic sea ice retreat, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50190.