Did unusually sunny skies help drive the record sea ice minimum of 2007?

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[1] We conduct experiments with an ice-ocean model to answer the question whether and to what degree unusually clear skies during the summer of 2007 contributed to the record sea ice extent minimum in the Arctic Ocean during September of 2007. Anomalously high pressure over the Beaufort Sea during summer 2007 appears associated with a strong negative cloud anomaly. This anomaly is two standard deviations below the 1980–2007 average established from a combination of two different satellite-based records. Cloud anomalies from the MODIS sensor are compared with anomalies from the NCEP/NCAR reanalysis and are found in good agreement in spatial patterns and magnitude. However, these experiments establish that the negative cloud anomaly and increased downwelling shortwave flux from June through August did not contribute substantially to the record sea ice extent minimum. This finding eliminates one aspect of the unusual weather that may have contributed to the record minimum. Citation: Schweiger, A. J., J. Zhang, R. W. Lindsay, and M. Steele (2008), Did unusually sunny skies help drive the record sea ice minimum of 2007?, Geophys. Res. Lett., 35, L10503, doi:10.1029/2008GL033463.

1. Introduction

[2] The extreme sea ice extent anomaly observed during the summer and fall of 2007 has presented the Arctic research community with a puzzle. The September 2007 sea ice extent minimum was 24% lower than the previous 2005 record and 37% lower than the 1979–2006 average [Comiso et al., 2008]. The decline in ice extent was considerably accelerated over recent trends, with September sea ice extent lower by four standard deviations over what would be expected from extrapolation of the 1980–2006 trend (H. Stern, personal communication, 2008). This raises the question: Does this extreme summer minimum reflect a warming trend, or is it the result of unusual weather in 2007? Significant climate events such as the ice retreat of 2007 also present an opportunity to systematically test and improve our understanding of the involved physical processes. The examination of relevant processes and their interplay is currently underway and various pieces of the puzzle are emerging. Thinning of sea ice over the last two decades provides an important piece of this puzzle [Maslanik et al., 2007]. Unusual wind patterns that advected ice from the Pacific to the Atlantic sector also appear to have contributed to the anomaly [Kwok, 2008]. Further, anomalous surface air temperatures have been cited as a potential cause [Comiso et al., 2008], though it is not clear at this point whether these are a cause or a response to the sea ice anomaly. Ocean surface temperatures were anomalously high [Steele et al., 2008] but their role in sea ice retreat is still unclear. Another explanation offered [Maslanik et al., 2007; Stroeve et al., 2008], presented on the NSIDC web site and reported frequently in the media, suggests that high-pressure and relatively clear skies from June through August of 2007 over the Beaufort sea region and the central Arctic increased downwelling solar radiation at the surface and accelerated sea ice melt. At first glance, this explanation appears plausible because of the timing and magnitude of the cloud anomaly. However, the exact location and timing of the anomaly are critical for making this explanation work. An examination of whether the cloud cover anomaly indeed fits into the sea ice anomaly puzzle seems to be in order. We therefore seek to determine whether skies were indeed unusually clear during the summer of 2007, and if so, how this contributed to the record ice extent minimum. The answer will be a step toward a comprehensive explanation of the extreme sea ice minimum of 2007.

[3] Speculation surrounding the role of clouds in causing the 2007 sea ice extent anomaly centered on the idea that a persistent high-pressure cell and relatively clear skies from June through August of 2007 caused an increase in downwelling shortwave fluxes which in turn helped accelerate melt. Figure 1a shows the sea level pressure anomaly for the summer (June–August) of 2007 relative to the 1980–2007 period. The air pressure at the center of the anticyclone is greater than two standard deviations above the mean and can therefore justifiably be termed “unusual.” Figure 1b shows cloud fractions over the Beaufort Sea region from June through August for 1980–2007. In order to obtain a sufficiently long record to assess the anomaly, cloud fractions from the TOVS Pathfinder Project [Schweiger et al., 2002] were combined with cloud fractions from the MODIS sensor (MOD08 product, Terra, version 5). Differences between the two data sets for the overlap period from 2000–2004 are small, therefore justifying this simple extension of the record. Cloud fractions over the Beaufort Sea region during summer of 2007 were 15% below the 1980–2007 mean. This anomaly exceeds two standard deviations of the interannual variation. Although the skies were far from clear (57%), cloud amounts for the summer of 2007 were indeed unusually low.

[4] In order to assess the total radiative effect of clouds, a diagnostic called “total cloud forcing” is often considered. Cloud forcing also helps address the typically opposing effects of clouds on downwelling short and longwave
radiative flux (hereafter, DSW and DLW). It represents the direct radiative effect of clouds on the surface radiation balance, typically calculated as the difference $F(a) - F(0)$, where $F(a)$ is the net surface radiation (given cloud fraction $a$) and $F(0)$ the total net surface radiation under clear skies. $F(0)$ is typically calculated using a radiative transfer model with no clouds. It is important to note that cloud forcing defined this way only addresses the direct radiative effect of clouds. Indirect effects, such as changes in the surface temperature in response to the cloud changes or changes in the cloud-base temperature in response to surface changes are excluded. Using this definition, an increase in net radiation (surface heat gain) with increasing cloud cover, represents a positive cloud forcing. The idea that unusually fewer clouds during the summer of 2007 accelerated ice melt and thus contributed to the record sea ice minimum assumes that total cloud forcing during the period was negative (a decrease in clouds produces an increase in the surface net radiative balance). This assumption seems valid, considering that results from SHEBA (Figure 2a) show that when surface albedo from an areal survey is used, total cloud forcing is negative for a period from late May through mid August [Intrieri et al., 2002]. Surface albedo plays a key role in cloud forcing. When albedo is high, changes in DSW have little impact on the net radiation balance. The fact that ice concentrations and thus surface albedo were already below normal in June, when the cloud anomaly began, further supports the idea that reduced cloud amounts accelerated sea ice melt and contributed to the sea ice extent anomaly.

Figure 1. (a) Sea level pressure anomaly for June–August 2007 from the NCEP/NCAR Renalysis-1 (relative to 1980–2007). The thick black contour delineates regions that are two standard deviations above the mean. (b) Cloud fraction over the Beaufort Sea region for June–August from the TOVS Polar Pathfinder data set and the MODIS –Terra. Dashed black lines indicate standard one and two standard deviations above and below the mean (dotted-line) over the 1980–2007 period. Total cloud fraction anomaly for June–August 2007 (relative to 2000–2006 period) (c) from MODIS data and (d) from NCEP reanalysis data.
Our approach to examining whether unusually clear skies indeed contributed to the sea ice extent anomaly of 2007 is to conduct a series of experiments with a coupled ice ocean model [Zhang and Rothrock, 2003]. These experiments consist of a control run in which the model is forced with radiative forcing fields that include the 2007 summer cloud anomaly, and sensitivity experiments in which the cloud anomaly is replaced with average conditions over the period 2000–2006. The use of a dynamic sea ice model allows us to assess the direct effect of the cloud anomaly on sea ice melt as well as indirect effects downstream from the anomaly.

2. Modeling Framework and Validation

The model is the Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS). It consists of a thickness and enthalpy distribution sea-ice model [Zhang and Rothrock, 2003] coupled with the Parallel Ocean Program (POP) ocean model. Lacking an atmosphere, the model is forced with daily NCEP/NCAR reanalysis-1 fields consisting of 10-m surface winds, 2-m surface air temperature, specific humidity, precipitation, evaporation, downwelling longwave radiation (DLW), sea level pressure (SLP), and cloud fraction. Cloud fraction is used to calculate downwelling shortwave radiation (DSW) following Parkinson and Washington [1979]. No data assimilation is used in this study.

Figures 2b and 3a demonstrate the ability of the model to simulate ice extent correctly. Figure 3a shows modeled and satellite observed ice concentration data. Ice concentration data are from data from NCEP (ftp://polar.ncep.noaa.gov/pub/cdas/). Modeled ice extent exceeds observations slightly, although there is a close match in the overall pattern. September ice extent is highly correlated with observations, with a linear correlation coefficient of 0.91 (Figure 2b). Comparisons of simulated ice thickness with observations from submarine sonar within the SCICEX area show a correlation of 0.71 with negligible bias. Simulated ice motion is validated through comparison with buoy tracks. The annual mean vector correlation for daily velocities is 0.88, with simulated ice speed exceeding observations by 8% on an annual average.

3. Forcing Fields and the 2007 Summer Cloud Anomaly

Biases in the NCEP fluxes occur, due to an underestimation of summer-time clouds. These biases are currently addressed in our model simulations by computing downwelling shortwave fluxes from NCEP/NCAR cloud fraction with a widely used parameterization [Parkinson and Washington, 1979]. The use of the parameterization reduces the summertime bias in the NCEP DSW and produces a better match with observations. Given the well-documented NCEP biases with respect to clouds and radiation [Liu et al., 2005; Makshtas et al., 2007; Serreze et al., 1998], the use of NCEP forcing fields to investigate the role of clouds may appear to be a rather poor choice. However, since the other alternative (ERA-40) ends in August of 2002, there currently is no other viable choice that would not require the construction of forcing fields from disparate sources and demand laborious retuning of the model. For the purpose of the specific question, whether “unusually sunny skies” contributed to the sea ice anomaly, NCEP forcing fields are adequate because cloud variability for the summer of 2007 is represented surprisingly well by the NCEP/NCAR reanalysis, as shown below.

Figures 1c and 1d show total cloud fraction anomalies for June–August 2007 observed from the MODIS sensor on Terra and computed by the NCEP/NCAR reanalysis model. Probably reflecting the strength of the pressure anomaly, the cloud anomalies are very similar, both in spatial pattern and magnitude. A strong negative anomaly extends from the North American continent over the Beaufort Sea towards the North Pole. This is the cloud anomaly mentioned in the literature [Maslanik et al., 2007; Stroeve et al., 2008]. There is a second, somewhat weaker, but positive cloud anomaly along the Russian sector of the Arctic Ocean. So, despite the fact that the summer cloudiness is typically underestimated by the NCEP reanalysis, the June–August cloud anomaly of...
Figure 3. (a) Control (CNTL) run ice concentration for Sept. 2007. Observed 15% ice concentration (ice edge) in black, (b) simulated sea ice concentration anomaly for September 2007, and (c) difference in ice concentration between the control run and the average SW fluxes run-(CNTL-AVSW). Note different color scale. Also shown are (d) difference in ice thickness for CNTL-AVSW, (e) ice concentration for CNTL-AVLW, and (f) ice concentration CNTL-AVSWLW.
2007 is captured quite well. The fact that NCEP cloud variability is better than one would expect considering the large summer bias, is further supported by the finding that despite biases, spatial patterns of cloud variability from different sources (ERA-40, NCEP, and AVHRR) for the SHEBA period [Liu et al., 2005] were quite similar. We therefore expect that anomalies in downwelling radiative fluxes due to cloud anomalies in the summer of 2007 are reasonably well captured in the forcing fields used for the control run. Sea ice parameters in the control run therefore incorporate the effect of the cloud anomaly, allowing experiments that will determine the magnitude of this effect.

4. Experiments

[10] Our numerical experiments consist of a control run (CNTL) in which the model is driven with 2007 atmospheric forcing data. A series of three “role of clouds” runs then replaces downwelling short and long-wave fluxes (individually and jointly) with average (2000–2006) conditions and the model is integrated over the period 1 January 2007 to 30 September 2007 using 1 January initial ice and ocean conditions from the control run. We call these runs AVSW (average DSW), AVLW (average DLW) and AVSWLW (average DSW and DLW).

[11] The first modified run simply addresses the question: To what degree did unusually clear skies in June–August 2007 and the resulting anomaly in DSW contribute to the sea ice extent anomaly of 2007? In this run (AVSW), the DSW fields for each day in 2007 are replaced with the corresponding daily averages over the 2000–2006 period. The remaining atmospheric forcing fields, as well as initial conditions, remained identical to the control run. The model was then integrated through September 2007. Figure 3b shows the September 2007 ice concentration anomaly (CNTL) and the differences (CNTL-AVSW) between the control run and the AVSW run. A comparison of Figure 3b and 3c shows that the shortwave anomaly does not correspond in location to the observed ice concentration anomaly. Figure 3c is plotted on a different scale to better illustrate the impact of the SW anomaly. It shows that even though the DSW anomaly had a small but noticeable impact on the September ice cover, there is very little spatial overlap between the control sea ice concentration anomaly and changes in ice concentration driven by DSW anomalies. DSW anomalies seem to have mostly affected areas north of 83° N. The extensive ice free areas in the Chukchi, East Siberian and Laptev Seas are unaffected by the DSW anomaly. The area of the ice concentration anomaly due to anomalous shortwave fluxes is largely contained within an area north of the ice edge. Anomalies in shortwave fluxes occurring during summer of 2007 therefore appear to have contributed little to the extreme minimum in ice extent.

[12] Although the effect of the DSW anomaly on ice concentrations and extent anomalies is small, ice thickness is reduced considerably in the AVSW run. The 2007 control run has substantially thinner ice (not shown) for large parts of the basin with ice thickness anomalies as large as ~1.5 m relative to the 2000–2006 mean. Figure 3d shows the ice thickness difference in September between the 2007 CNTL and the averaged DSW (AVSW run). The impact of the DSW anomaly on the ice thickness is substantially greater than on the ice concentration with reductions up 0.7 m. However, thickness changes in the AVSW run are also confined to areas well north of the 2007 September ice edge and thus did not contribute to the ice retreat. The AVSW experiment purposefully ignores simultaneous changes in DLW associated with the cloud anomaly. Because those are of opposite sign, the AVSW experiment establishes an upper bound for the “sunny skies” hypothesis.

[13] In order to examine the role of DLW anomalies in driving the record sea ice extent minimum, we conduct an analogous run in which DLW fields are substituted with corresponding fields obtained by averaging daily fields over the 2000–2006 period. Results from this run, AVLW, are shown in Figure 3e. A comparison of this difference pattern with the ice concentration anomaly in the control run shows considerably greater impact and overlap with the 2007 summer ice concentration anomaly than the AVSW experiment. DLW anomalies contributed to a substantial decrease in ice concentration of 10–20% just south of the ice edge on the Siberian side of the Arctic. These areas are cloudier than average in 2007 rather than clearer (Figure 1c).

[14] To assess the total effect of downwelling radiation anomalies we conducted a third run (AVSWLW). In this run both, DSW and DLW fields were replaced with their corresponding averages. The combined effect of shortwave and long-wave anomalies is shown in Figure 3f. Given the small response in the AVSW experiment, it is not surprising that the response is indistinguishable from the LW experiment.

5. Discussion and Conclusions

[15] Our model experiments clearly demonstrate that DSW anomalies associated with clearer skies during June and July 2007 did not contribute significantly to the record sea ice minimum of 2007. The impact of DSW anomalies is small and confined to areas north of the ice edge. The geographical distribution of the cloud anomalies, with negative anomalies over the Beaufort Sea and over the Canadian Basin, and positive anomalies over the Siberian sector of the Arctic Ocean are responsible for this small response. On the other hand, anomalies in DLW fluxes occurring at the same time and location as the positive cloud anomaly may have contributed to the record minimum. DLW anomalies account for a reduction in 20% ice concentration just south of the ice edge. Given that during this time cloud forcing is negative, (an increase in clouds decreases net radiation), this result seems counterintuitive. The explanation is that DLW fluxes are not only affected by clouds but also by changes in air temperature and humidity. Surface air temperatures in the area just south of the ice edge were up to 5 K warmer than the 1980 to 2007 average. This warming maybe a response to changes in cloud cover (fraction, properties), heat advection, or heat fluxes from the exposed ocean. Because surface temperature advection in the NCEP/NCAR reanalysis fields does not appear to be anomalous during the summer of 2007, local heating in response to the removal of sea ice is the more likely reason for the increase in temperature. Radiative transfer calculations show that the effect of this warming on DLW is greater than the reduction in total downwelling radiation due to the positive cloud anomaly. However, the total “cloud impact”
also depends on the accurate characterization of the compensating cloud effects on downwelling short and longwave radiation and the net radiation balance. This balance is susceptible to errors in forcing fields and model generated albedo and surface temperature.

[16] An important limitation of our experiments is that there is no feedback between atmosphere and surface. Although changes in downwelling long and shortwave fluxes will produce a response in surface fluxes in our experiments, such changes in surface fluxes cannot feed back to the atmosphere.

[17] In summary, while we are able to conclude that “sunny skies” during the summer of 2007 did not contribute substantially to the sea ice extent anomaly, the assessment of the total impact of clouds awaits further investigation. In the context of the question of whether the record sea-ice extent minimum is attributable to longer-term warming or unusual weather during 2007, our finding that “sunny” weather was not a necessary factor, appears to be a meaningful step. However, our finding that sea ice was thinned by unusually sunny skies over some areas where it survived the summer of 2007 suggests a potentially greater vulnerability of the ice in these regions for subsequent melt seasons.

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References


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