GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L11501, doi:10.1029/2008GL034007, 2008

Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007

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Received 15 March 2008; revised 23 April 2008; accepted 2 May 2008; published 3 June 2008.

[1] The summer extent of the Arctic sea ice cover, widely recognized as an indicator of climate change, has been declining for the past few decades reaching a record minimum in September 2007. The causes of the dramatic loss have implications for the future trajectory of the Arctic sea ice cover. Ice mass balance observations demonstrate that there was an extraordinarily large amount of melting on the bottom of the ice in the Beaufort Sea in the summer of 2007. Calculations indicate that solar heating of the upper ocean was the primary source of heat for this observed enhanced Beaufort Sea bottom melting. An increase in the open water fraction resulted in a 500% positive anomaly in solar heat input to the upper ocean, triggering an ice–albedo feedback and contributing to the accelerating ice retreat.

Citation: 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.

1. Introduction

[2] The summer extent of the Arctic sea ice cover, widely recognized as an indicator of climate change [*Arctic Climate Impact Assessment*, 2005], has been declining for the past few decades. In September 2007 it reached a record minimum of 4.2 million km^2, which was 1.6 million km^2 or 23 percent less than the previous record set in September 2005 [*Stroeve et al.*, 2008]. The retreat was particularly pronounced in the East Siberian, Chukchi, and Beaufort Seas.

[3] There are several possible causes of the dramatic loss, each of which has implications for the future trajectory of the Arctic sea ice cover. Earlier work has established the general impact on ice extent of warming trends [*Johannessen et al.*, 2004], changes in atmospheric circulation [*Rigor and Wallace*, 2004; *Maslanik et al.*, 2007], increased export of older ice out the Fram Strait [*Nghiem et al.*, 2007], low clouds [*Francis and Hunter*, 2006], advection of ocean heat from the Pacific [*Woodgate et al.*, 2006; *Shimada et al.*, 2006] and North Atlantic [*Polyakov et al.*, 2007], and enhanced solar heating of the ocean [*Perovich et al.*, 2007].

[4] Observations of the amount of melting at the top and bottom surfaces of the Arctic sea ice cover provide insight into the nature of the observed decline in its extent. Such measurements can be made during field experiments [*Untersteiner*, 1961; *Perovich et al.*, 2003] or by using autonomous ice mass balance buoys [*Richter-Menge et al.*, 2006]. Top melting is determined by the net surface heat budget of the ice and thus includes changes due to radiative forcing and air temperature. Bottom melting is determined by the amount of heat in the upper ocean and the transfer of that heat to the underside of the ice. A time series of observed ice melt can provide perspective on changes in the surface and ocean heat budgets.

[5] In this paper we present ice mass balance observations from the Beaufort Sea and North Pole regions for several years. These observations indicate that there was an extraordinarily large amount of bottom melting of the ice in the Beaufort Sea in the summer of 2007 and that solar heating of the upper ocean was the primary heat source.

2. Results and Discussion

[6] Observations of ice growth and surface and bottom melt have been made from autonomous ice mass balance buoys (IMB) [*Richter-Menge et al.*, 2006] that drifted with the ice pack. These buoys are equipped with a datalogger, satellite transmitter, barometer, acoustic rangefinders placed above the ice surface and below the ice bottom, and a thermistor string extending from the surface through the snow and ice into the upper ocean [*Perovich and Richter-Menge*, 2006; *Richter-Menge et al.*, 2006]. The IMBs provide information on snow accumulation and melt, ice growth and decay, the onset dates of melt and freezeup, and the ocean heat flux. While these observations are point measurements, they have been shown to represent aggregate-scale conditions [*Perovich and Richter-Menge*, 2006].

[7] Figure 1 presents observations of surface and bottom melt from 1994 to 2007 in two regions: the Beaufort Sea and the vicinity of the North Pole (Figure 1 (bottom)). The average annual surface melt is greater in the Beaufort Sea (0.64 m) than near the North Pole region (0.26 m) because incident solar radiation is greater at the lower latitude of the Beaufort Sea. Both top and bottom melting exhibit interannual variability. Despite the extreme retreat of the ice cover during 2007, the amount of surface melt in both regions was not significantly different in 2007 compared to earlier years. Bottom melting at the North Pole in 2007 was also comparable to earlier years. In sharp contrast, there was a dramatic increase in bottom melting in the Beaufort sector in 2007.

[8] The 2.10 m of bottom melt in 2007 in the Beaufort Sea was more than six times the annual average value of 0.34 m for the 1990s and two and a half times the 2006

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0094-8276/08/2008GL034007$05.00

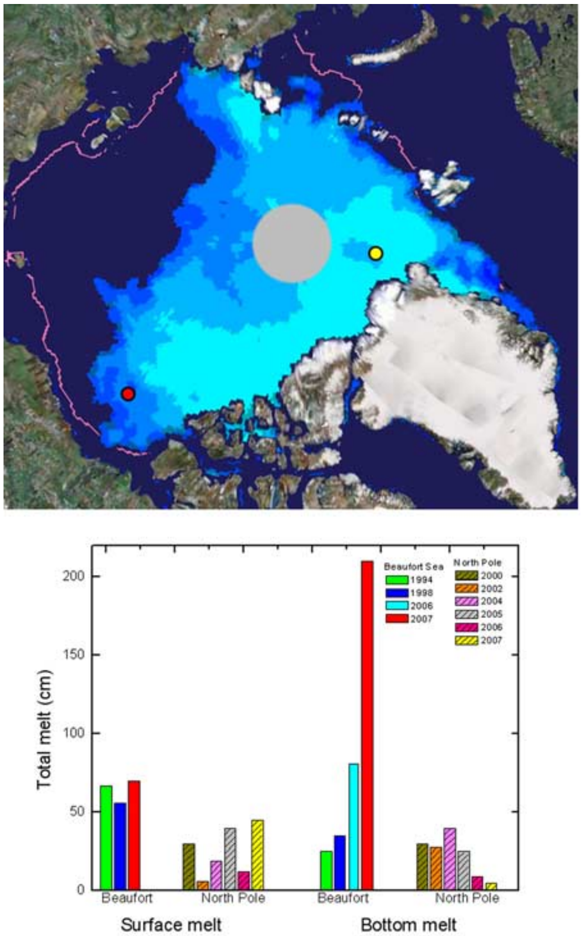

Figure 1. (top) The ice extent on 27 August 2007 courtesy of the National Snow and Ice Data Center and Google maps. The shades of blue show the percent area covered by ice from 0% (dark) to 80–100% (light). The red dot is the position of the Beaufort Sea buoy, and the yellow dot is the position of the North Pole buoy. (bottom) Observations of total surface and bottom melting in different years in the Beaufort Sea and North Pole regions.

result. This observation indicates that bottom melting was a major contributor to the 2007 ice loss in the Beaufort Sea. Details of the Beaufort results are presented in Figure 2, which shows the annual cycle of temperature and mass balance from August 2006 through December 2007. For the most part, conditions were typical of thick (3.2 m) multiyear ice in this region: minimum winter air temperatures of −45°C, snow depth of 0.4 m, winter ice growth of 0.33 m, and onset of melt in early June. What was extraordinary was the rapid bottom melting. In the month of August, bottom melting averaged 4 cm per day and reached maximum values of 11 cm per day in the last week of August, compared to characteristic averages of about 1 cm per day for this region [*Perovich et al.*, 2003].

[9] The extreme amount of bottom melting observed in 2007 required considerable heat from the upper ocean. Earlier work has established the importance of solar heating of open water on bottom melting of the ice [*Maykut and McPhee*, 1995; *Perovich*, 2005]. We believe that solar radiation deposited in areas of open water was a primary source of the large amount of ocean heat in 2007. Open water reflects only 7% of the incident solar radiation, compared to 85% for snow-covered sea ice and 65% for bare sea ice. As the ice cover decays, highly reflecting ice is replaced by highly absorbing ocean, resulting in more solar heat absorption and more melting. Furthermore, an ice cover thinned by excessive bottom melt transmits more solar radiation directly to the ocean than the original thicker ice cover. This is the classic ice–albedo feedback mechanism.

[10] The solar heat input directly to the upper ocean (F_{rw}) can be estimated using the relationship

$$F_{rw} = F_r(1 - \alpha_w)A_w, \qquad (1)$$

where F_r is the incident solar irradiance, α_w is the albedo of the ocean, and A_w is the fractional area of ice-free ocean. This relationship represents a lower bound on the solar heat input to the upper ocean, as it does not consider the contribution from sunlight penetrating through the ice cover into the ocean.

[11] Using Equation 1, daily values of F_{rw} from 1 January 2007 to 21 September 2007 were computed on a 25-km × 25-km grid over the entire Arctic Ocean and adjacent seas. The daily values were then integrated over the entire time period to get the cumulative solar heat input. The ocean albedo was set to 0.07 based on observations by *Pegau and Paulson* [2001]. Values of A_w were obtained from passive microwave satellite data and F_r from operational products of the European Center for Medium Range Weather Forecasts. The cumulative solar heat directly input to the ocean from 1 January to 22 September in 2007 was compared to values for the same time interval averaged over the years 1979–2005 [*Perovich et al.*, 2007].

[12] Figure 3 shows the percent anomaly for 2007 compared to the 1979–2005 average. The ice mass balance buoy drift track is plotted in black. The 2007 solar heat input in the buoy drift area was 400–500% higher than average. This anomaly can only result from changes in incident solar irradiance or in the area fraction of open water (Equation 1); changes in ice thickness or pond cover would not affect this calculation. The incident solar irradiance anomaly in June through August 2007 was only 6%, indicating that the positive solar heat input anomaly was due to the larger-than-average fraction of open ocean area in this region (A_w). The 2007 ocean area fraction was 0.34 in July and 0.51 in August 2007, compared to 1979–2005 mean July and August values of 0.19 and 0.26, respectively. Thus the positive anomaly in solar heat input was due to an almost doubling of the area fraction of open water in 2007 compared to the prior climatology.

[13] Calculations confirm that solar heating due to open water was sufficient in magnitude and in timing to produce the observed bottom melting (Figure 4). Indeed, the anomalously large areas of open water absorbed twice as much heat as was needed for the observed bottom melting. Again, it is important to note that this represents a lower bound on the solar heat absorbed in the ocean as there was also a contribution from sunlight transmitted through the ice. This contribution will increase as the ice becomes thinner and more ponded [*Perovich et al.*, 2007]. There was ample

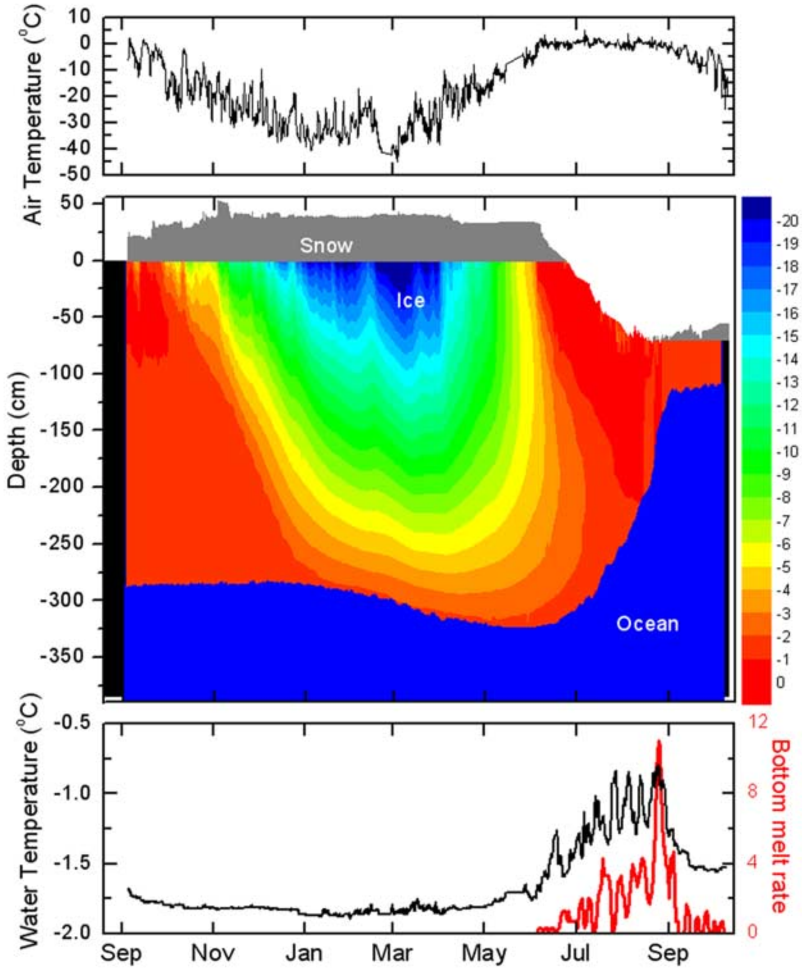

Figure 2. Time series from August 2006 to October 2007 from the Beaufort Sea ice mass balance buoy. (top) Air temperature. (middle) Internal ice temperature using color contours, with blue being cold and red warm. The gray shaded area represents snow, the black areas represent missing data, and the dark blue represents the ocean. (bottom) Upper ocean temperature near the bottom of the ice (black) and the bottom melt rate (red) in cm per day. Bottom melt rates were smoothed using a three-day running mean.

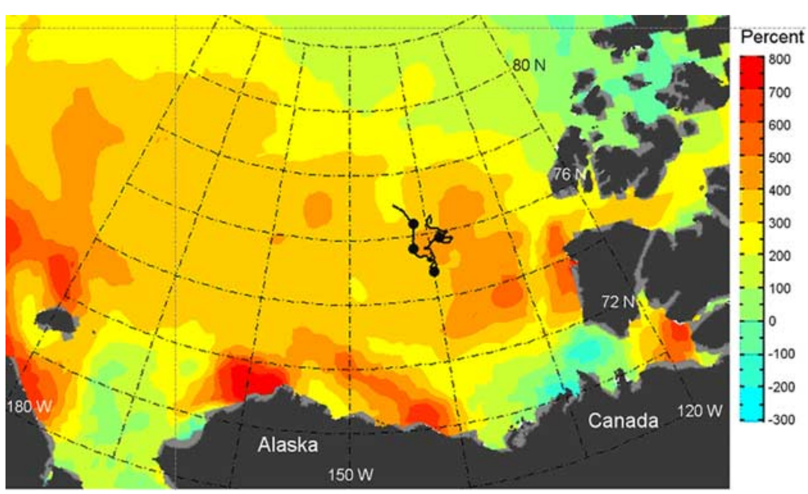

Figure 3. Anomaly of 2007 total (1 January through 21 September) cumulative solar heat input directly into the ocean compared to the average from 1979 to 2005. The black line designates the drift track of the ice mass balance buoy from 1 June to 21 September 2007. The four dots denote positions from mid-July to mid-September that were averaged to calculate the time series in Figure 4.

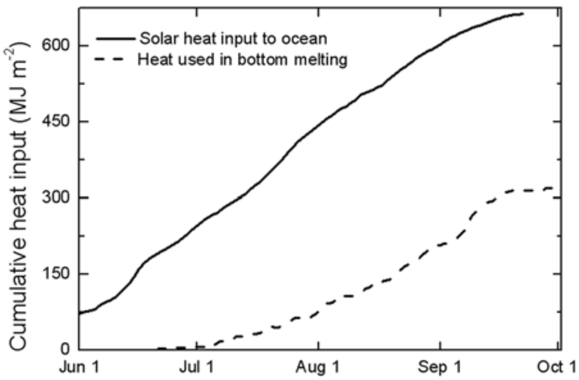

Figure 4. Results from the Beaufort Sea in 2007. The dashed line shows the time series of the heat required for the observed bottom melting, and the solid line shows the solar heat directly input to the ocean in the region defined by the average of the four points in Figure 3.

residual heat for lateral melting of ice floes and general warming of the upper ocean, both of which are likely to further hasten the decay of the Arctic sea ice cover. Lateral melting increases the area of open water and consequently the solar heat input, affording a positive feedback. Warming of the upper ocean retards freezing and extends the impact of summer heat input into the fall and winter. For example, the excess solar heat in Figure 4 is sufficient to warm the upper 5 m of the ocean by 5°C. The impact of this heating is evident in the observed warming of the upper ocean [*Steele et al.*, 2008] and the slow recovery of the ice cover in this region during the 2007 fall freezeup [*Comiso et al.*, 2008]. Combining results from this analysis with oceanographic observations will delineate the relative contributions of local solar heating and advected ocean heat from lower latitudes.

3. Conclusions

[14] There was an extraordinarily large amount of ice bottom melting in the Beaufort Sea region in the summer of 2007. Solar radiation absorbed in the upper ocean provided more than adequate heat for this melting. An increase in the open water fraction resulted in a 500% positive anomaly in solar heat input to the upper ocean, triggering an ice–albedo feedback and contributing to the accelerating ice retreat. The melting in the Beaufort Sea has elements of a classic ice–albedo feedback signature: more open water leads to more solar heat absorbed, which results in more melting and more open water. The positive ice–albedo feedback can accelerate the observed reduction in Arctic sea ice. Questions remain regarding how widespread this extreme bottom melting was, what initially triggered the increase in area of open water, and what the summer of 2007 portends for 2008 and beyond.

[15] **Acknowledgments.** Financial support was provided by the National Science Foundation Arctic Program, the National Oceanic and Atmospheric Administration Arctic Research Office, and the NASA Cryospheric Sciences Program. We thank Bruce Elder and Keran Claffey for their assistance with the ice melt observations, Kay Runciman for incident solar radiation data and ice concentration data, and Matthew Sturm for many helpful suggestions.

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