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Key Points:
- There is large interannual variability in sea ice melt in the study region
- Bottom melting has increased in recent years
- At the end of summer melt, ice in this region is still over 1 m thick

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Sea ice mass balance observations from the North Pole Environmental Observatory

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Abstract In recent years the periphery of the Arctic sea ice cover has undergone significant changes, with a reduction in summer ice extent, a thinning of the ice, and a shift from multiyear to first year ice. Here we examine sea ice conditions during nine summers between 2000 and 2013 in the interior of the ice pack, using autonomous measurements of sea ice mass balance deployed near the North Pole. Results exhibit no definitive trends. There is large interannual variability, with surface melt ranging from 0.02 m to 0.50 m and bottom melt from 0.10 m to 0.57 m. The largest amounts of bottom melt have occurred in the past few years. For all 9 years the ice at the end of the melt season was at least 1.2 m thick.

1. Introduction

There have been profound changes in the Arctic sea ice cover in recent years. Record September minimum ice extents were observed in 2005, 2007, and 2012 [*Comiso*, 2012; *Cavalieri and Parkinson*, 2012; *Serreze et al.*, 2007; *Stroeve et al.*, 2007, 2012]. The 2012 extent of 3.4 million km^2 was only 55% of the 1981–2010 average of 6.2 million km^2 [*Jeffries and Richter-Menge*, 2013]. While there was a substantial increase to 5.1 million km^2 in the 2013 minimum ice extent, the overall trend is still strongly downward. Submarine, aerial electromagnetic surveys, and satellite observations have shown a decrease in ice thickness [*Rothrock et al.*, 2008; *Giles et al.*, 2008; *Haas et al.*, 2008; *Kwok and Rothrock*, 2009; *Kwok et al.*, 2009; *Haas et al.*, 2010; *Laxon et al.*, 2013]. Large reductions in March ice thickness have been observed in the southern Beaufort and Chukchi Sea region in recent years, while conditions in the central Arctic have remained consistent [*Richter-Menge and Farrell*, 2013]. There has also been a shift from primarily perennial ice pack to seasonal ice [*Maslanik et al.*, 2011; *Nghiem et al.*, 2007]. Large decreases in summer sea ice coverage have been observed, particularly in the peripheral seas of the western Arctic (Beaufort, Chukchi, East Siberian, and Laptev). *Zhang et al.* [2013] demonstrated how storm-induced vertical mixing of ocean could greatly increase bottom melting.

The observed decreases in the Arctic sea ice cover are due to many factors [*Serreze et al.*, 2007]. Contributions to ice loss include warming [*Overland et al.*, 2008], atmospheric circulation and ice motion changes [*Rampal et al.*, 2009; *Hutchins and Rigor*, 2012], shifts in cloud cover [*Kay et al.*, 2008; *Schweiger et al.*, 2008], advected ocean heat [*Polyakov et al.*, 2010; *Woodgate et al.*, 2010], heat from river discharge [*Nghiem et al.*, 2014], and the ice albedo feedback [*Perovich et al.*, 2007, 2008]. These sea ice losses have brought into question the long-term survivability of the summer ice cover.

Here we consider ice conditions in a region between the North Pole and the Greenland Sea, which remains dominated by thicker, multiyear ice. We examine results from autonomous sea ice mass balance buoys operating during the summer from 2000 to 2013 [*Richter-Menge et al.*, 2006]. The one-dimensional mass balance measured by the buoys documents the amount of ice growth and snow accumulation in the winter and the amount of surface and bottom melt in the summer. These measurements integrate both the surface and the bottom heat budgets of the ice cover, thus providing insight into the timing and magnitude of atmospheric and oceanic forcing. Annual ice losses due to summer surface and bottom melt and trends over the past 14 years are examined.

2. In Situ Sea Ice Mass Balance Observations

Autonomous ice mass balance buoys (IMB) have been deployed in the sea ice cover at the North Pole Environmental Observatory (NPEO) [*Morison et al.*, 2002] every April since 2000. These buoys measure the sea

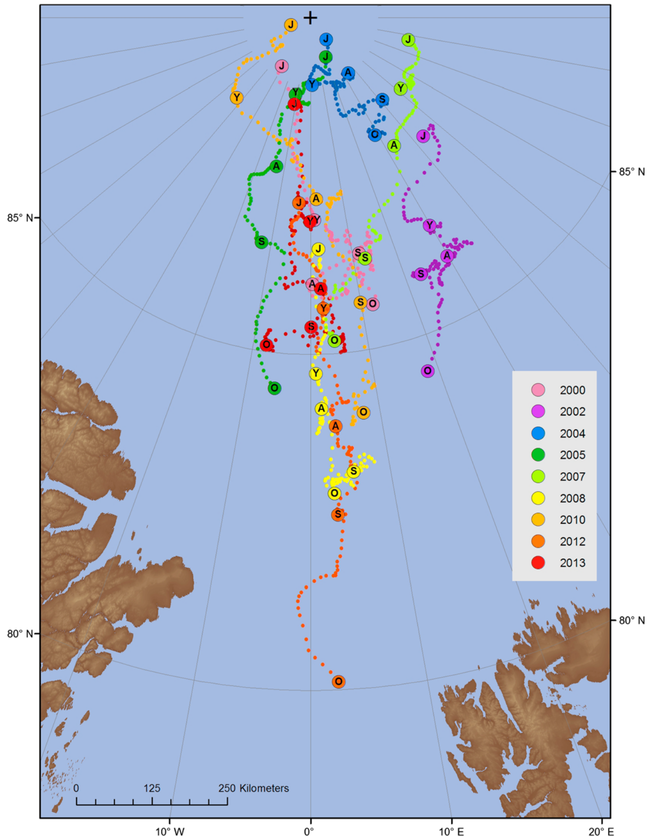

Figure 1. Drift tracks of IMBs during the melt season from 1 June to 1 October. The black cross is the North Pole. Parts of Greenland and Svalbard are on the lower left and right, respectively.

ice mass balance using sensors monitoring changes in snow deposition and ablation, ice growth, and ice surface and bottom melt [*Richter-Menge et al.*, 2006; *Perovich and Richter-Menge*, 2006]. We present ice mass balance results from nine summers from 2000 to 2013. Buoys from four other summers within this period were lost due to ice conditions, wildlife, and instrument failures.

IMBs discussed in this paper were all deployed near the North Pole in April. Each IMB was installed in sea ice that was typical of ice in the region, avoiding both relatively thin ice and deformed ice. While these buoys were deployed near the North Pole, because they are installed in floating sea ice, they drifted south, ultimately exiting out through the Greenland Sea. The drift tracks of the buoys from 1 June to 1 October are displayed in Figure 1. Buoy positions on the first of each month are noted. The general drift direction is always south toward the Greenland Sea.

3. Results and Discussion

Results from the nine IMBs are summarized in Table 1. Since the buoys were installed in April, there was only modest ice growth before the onset of melt in June. The maximum ice thickness at melt onset ranged from 1.77 m (2010) to 2.80 m (2012), with maximum snow depths from 0.04 m (2008) to 0.38 m (2012). In all cases, the ice cover was still substantial at the end of summer melt with thicknesses from 1.25 (2000 and 2008) m to 2.60 m (2004). Unlike ice in other regions, such as the Beaufort Sea [*Barber et al.*, 2009; *Perovich et al.*, 2008] that have seen major ice melt and deterioration, the ice cover in this region of the central Arctic (Figure 1) is still robust at the end of summer melt.

Figure 2 summarizes surface and bottom melt for the 9 years of observations. The snow melt is expressed in terms of the ice equivalent snow melt (S_i) using the expression

$$S_i = (\rho_s/\rho_i)H_s,$$

where H_s is the snow depth, ρ_s is the snow density set to 300 kg m^{-3}, and ρ_i is the ice density set to 900 kg m^{-3}. The large amount of interannual variability in both surface and bottom melt is evident in the figure. While the snow completely melted in all cases, there was great interannual variability in the amount of surface ice melt, ranging from as little as 0.02 m in 2010 up to 0.50 m in 2007. Bottom melt showed similar variability ranging from 0.10 m (2004) to 0.57 m (2012). The total amount of snow (ice equivalent) and ice melt varied by a factor of 5 from 0.23 m in 2004 to 1.13 m in 2012, averaging 0.66 m.

While there is tremendous year to year variability in the amount of surface melt, no trend is evident. There does, however, seem to be an increase in the amount of bottom melt. The four largest bottom melts occurred from 2008 to 2013. The average bottom melt was 0.48 m for this period and was more than twice the 2000–2005 average of 0.22 m. Should this increase in bottom melt continue, it would have repercussions for the health of the ice cover.

Table 1. Summary Table for Sea Ice Mass Balance Measurements[a]

Year	Period of Operation	1 June Latitude	1 June Longitude	1 September Latitude	1 September Longitude	Maximum Snow Depth	Ice Growth	Maximum Ice Thickness	End of Melt Thickness	Total Ice Melt	Snow Melt	Ice Surface Melt	Total Surface Melt	Ice Bottom Melt	Start Snow Melt	Start Surface Ice Melt	End Surface Ice Melt	Days Surface Melt
2000	Apr 2000–Nov 2000	89.2°	30.4°W	86.3°	8.9°E	30	5	185	125	60	30	30	39	30	15 Jun	25 Jun	10 Aug	56
2002	Apr 2002–Nov 2002	87.6°	43.9°E	85.9°	22.8°E	31	10	255	212	43	31	15	24	28	11 Jul	6 Aug	23 Aug	43
2004	Apr 2004–Dec 2004	89.6°	35.8°E	88.5°	17.8°E	35	0	272	260	12	35	2	13	10	12 Jun	23 Jul	4 Aug	53
2005	Apr 2005–Nov2005	89.4°	21.7°E	87.5°	20.9°W	20	10	230	170	60	20	40	46	20	1 Jun	10 Jun	20 Aug	80
2007	Apr 2007–Dec 2007	88.5°	77.9°E	87.2°	26.1°E	15	16	223	158	65	15	50	55	15	5 Jun	20 Jun	15 Aug	71
2008	Apr 2008–Nov 2008	86.6°	1.9°W	83.2°	5.6°E	4	10	199	125	74	4	22	23	52	10 Jun	20 Jun	1 Aug	52
2010	Apr 2010–Dec 2010	88.4°	43.2°W	83.1°	6.0°E	36	7	177	130	47	36	2	13	45	13 Jun	29 Jun	1 Jul	18
2012	Apr 2012–Oct 2012	87.3°	3.6°W	83.5°	5.2°E	38	6	280	178	102	38	45	56	57	1 Jun	11 Jul	6 Aug	66
2013	Apr 2013–Dec 2013	88.7°	11.7°W	85.3°	0.1°W	14	18	218	158	60	14	22	26	38	8 Jun	9 Jul	19 Aug	72

[a]All thicknesses, growth, and melt data have units of centimeters.

The relative amounts of surface and bottom melt are compared in the scattergram in Figure 3. There is no obvious correlation between surface and bottom melt and the coefficient of determination (R^2) is 0.00. In 4 years there was more surface melt (2000, 2004, 2005, and 2007), in 4 other years there was more bottom melt (2002, 2008, 2010, and 2013), and in 2012 surface and bottom melt were essential equal. In some years there was actually an inverse relationship between surface and bottom melt, with one large and the other small (e.g., 2005, 2007, 2008, and 2010).

The ice mass balance observations show significant ice remaining at the end of summer, large interannual variability in melt, and no strong connection between the amount of surface and bottom melt. These results raise three questions: (i) Why is the large melt observed in locations such as the Chukchi and Beaufort Seas not occurring in our study region? (ii) What is driving the interannual variability? and (iii) Is summer melt near the North Pole correlated with large-scale changes in the sea ice cover?

Large amounts of surface and bottom melt have been observed in the Beaufort Sea, often resulting in the complete regional loss of the ice cover. Why has this not been observed at the North Pole? At least part of the reason is solar radiation. At the North Pole there is less incident shortwave irradiance, particularly in spring and early summer. Using results from the ERA-40 reanalysis, we calculated the average incident solar irradiance in the Beaufort Sea (76.9°N, 165°W) and near the North Pole (89.1°N, 0°E) averaged from 1979 to 2011. Integrated over the entire year the incident solar irradiance was 2770 MJ m^{-2} in the Beaufort Sea and 2340 MJ m^{-2}

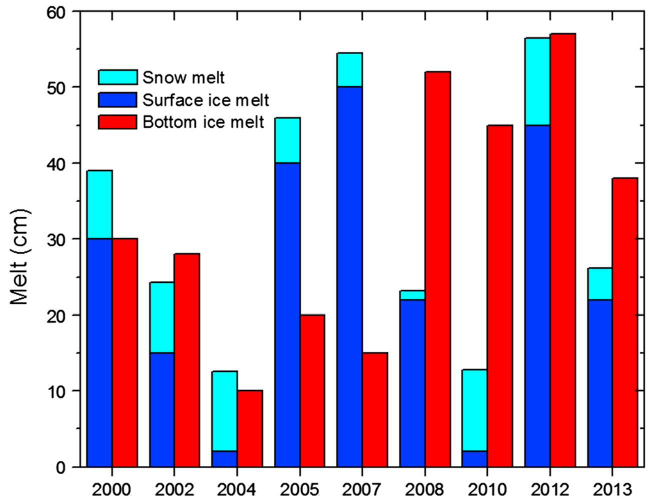

Figure 2. Histogram of surface ice melt (blue), ice equivalent snow melt (cyan), and bottom ice melt (red) for nine ice mass balance buoys.

near the North Pole. The difference in incident irradiance is 431 MJ m^{-2}, with 265 MJ m^{-2} of this difference deposited in the spring and early summer prior to 30 June each year. Less incident shortwave likely leads to less heat deposited in the ice and upper ocean and, hence, less melting.

Relationships between surface and bottom melt and three possible driving factors (ice extent, Arctic Oscillation index, and buoy latitude) are explored in Figure 4. The change in ice extent between March and September is a measure of the overall amount of ice loss that occurred Arctic wide during summer. Previous studies [*Rigor et al*., 2002; *Maslanik et al*., 2007] have explored the connection between the Arctic Oscillation index and ice extent. We compare melt to the Arctic Oscillation index averaged from June through August. The IMB latitude on 1 September is a measure of both how far south the buoy drifted and how fast it traveled during the summer. Bottom melt has also been related to the amount of open water and solar heat input to the upper ocean [*Perovich et al*., 2008, 2011]. Unfortunately, this relationship could not be examined for the NPEO ice mass balance buoys, since they were too far north for passive microwave satellite observations of ice concentration.

Surface melt does not correlate with any of the three factors. There is considerable scatter in all three surface melt plots, and values of R^2 are small (0.01 to 0.16). Surface melt is also not correlated with the total incident shortwave irradiance from 1 June to 1 September. There is a modest correlation ($R^2 = 0.48$) between the amount of surface melt and the length of the melt season. We also expect surface melting to be influenced by the intensity of the melt season, the timing of the melt season, the amount of snow cover, and the longwave and turbulent fluxes. Bottom melt shows a modest correlation with change in ice extent, with 2007 as a major outlier. An examination of the details of the 2007 ice mass balance record shows that a false bottom may have been present at the underside of the ice for much of July. A false bottom is an ice layer that forms beneath the ice bottom at the interface between fresh meltwater and saline ocean water [*Notz et al*., 2003]. A false bottom isolates the true ice bottom from the ocean thereby limiting the amount of bottom melt. Removing the 2007 point increases R^2 from 0.51 to 0.79 indicating that large decreases in overall ice extent are associated with increased amounts of bottom melt at the NPEO sites (Figure 1). Bottom melt is uncorrelated with average Arctic Oscillation index ($R^2 = 0.10$). The strongest relationship is between bottom melt and 1 September latitude ($R^2 = 0.92$). Bottom melt increased linearly with the distance of the southward transit by 1 September. The increase in bottom melt was 0.08 m per degree of latitude. Increased bottom melt was likely a result of increased solar heat deposited in the upper ocean [*Perovich et al*., 2011].

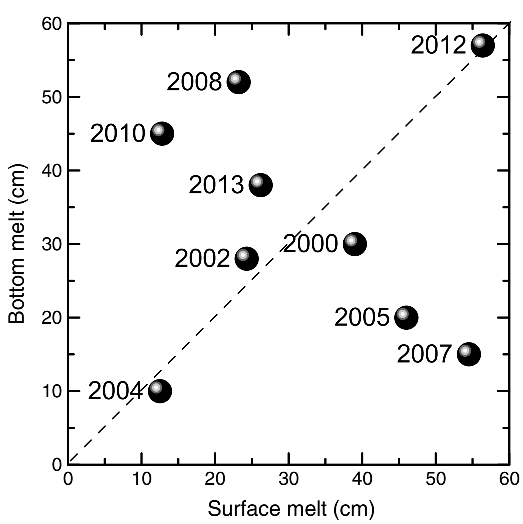

Figure 3. Scattergram of surface ice melt versus bottom ice melt. The dashed line shows a 1:1 surface to bottom melt relationship.

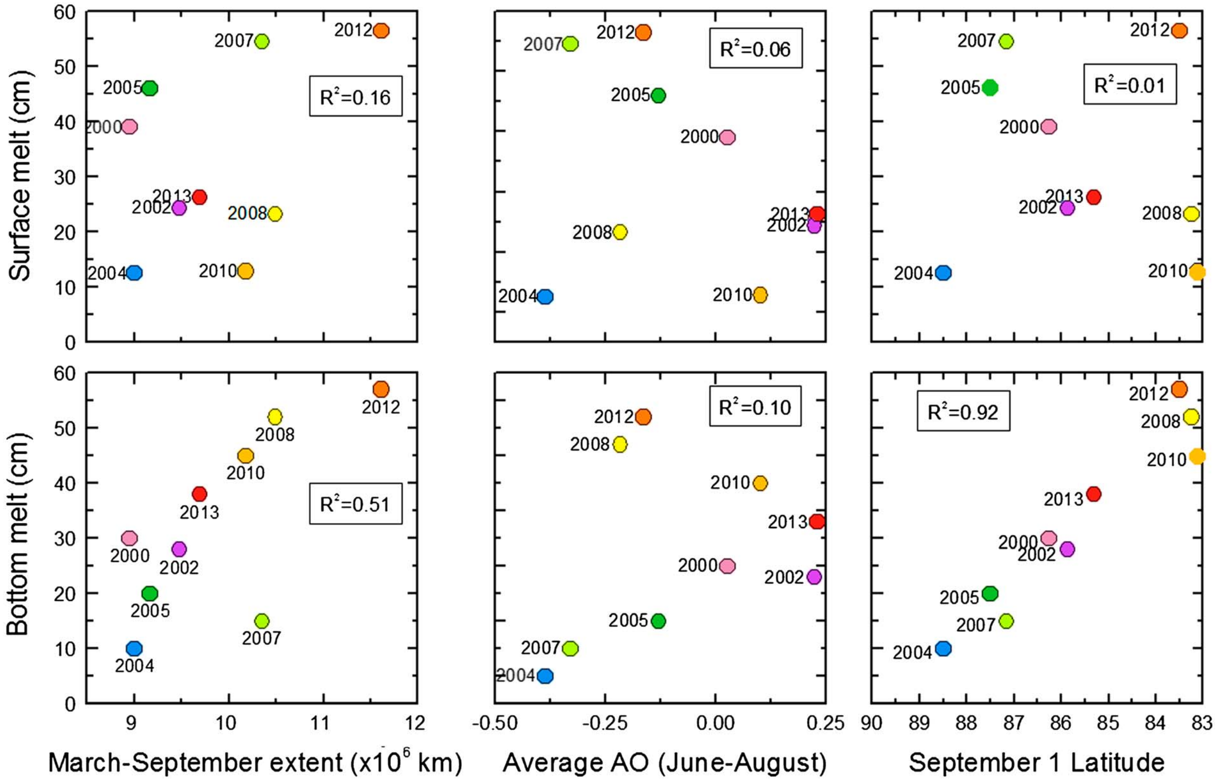

Figure 4. Scattergrams of surface and bottom melt versus (left column) change from March to September ice extent; (middle column) average summer (1 June to 1 September) Arctic Oscillation index; and (right column) latitude of ice mass balance buoy on 1 September. The colors correspond to the drift tracks in Figure 1.

Multiple factors, including others not explored here, may be influencing surface and bottom melt, but with only nine data points; opportunities for multiple regression analysis are limited. Focusing on the two most recent record-setting minimum ice extent years, 2007 and 2012, 2012 had the largest amount of surface melt and 2007 was a close second. The largest amount of bottom melt was observed in 2012, but 2007 was the second smallest bottom melt, likely influenced by the false bottom mentioned above. Even in these years, however, the NPEO ice was still more than 1.5 m thick at the end of summer melt.

What conditions and forcing would it take to melt the North Pole ice? A general trend of warmer air temperatures would gradually increase surface melt, and over time this could result in the complete loss of the summer ice cover in this region. Based on ice mass balance observations in other regions, however, rapid sea ice loss is typically associated with large increases in bottom melt. The upper ocean heat driving the bottom melt can either be advected from other regions or be locally deposited solar radiation [*Perovich et al.*, 2008; *Woodgate et al.*, 2010]. It follows that decreased summer ice concentration in the North Pole region would result in more solar heat deposited in the upper ocean and increased melting. Changes in the character of the ice being advected into the North Pole region, to include increased first year ice and/or thinner ice, could also play an important role in changing the resilience of ice in this region. A shift to first year ice will result in more ponding and enhanced solar absorption in the ice and upper ocean [*Perovich and Polashenski*, 2012].

Even though the ice at the North Pole in April survives summer melt, it does not last until the next spring. The ice is in transit, headed from the North Pole area in April to the Greenland Sea and eventually out the Fram Strait. When the ice enters Fram Strait several months later, between December and March, contact with warm Atlantic waters results in complete ice melt, even in midwinter.

4. Conclusions

There has been considerable discussion in recent years about the potential for an Arctic with no sea ice in summer. Overall, ice conditions at the North Pole have changed much less than in the Arctic's peripheral seas.

At least under the present conditions, summer sea ice in the general vicinity of the North Pole is surviving summer melt. For the 9 years studied from 2000 to 2013, ice thickness at the end of melt season was at least 1.2 m. At the high latitudes near the North Pole, the incident solar radiation is less than in more southern regions, such as the Beaufort Sea, and melting is less. Additionally, the North Pole region currently remains removed from peripheral seas and marginal ice zones, from where large amounts of ocean heat could be advected.

While results from 2000 to 2013 exhibit no definitive trends in surface and bottom melt, there are a number of interesting findings. There is large interannual variability, with surface melt ranging from 0.02 m to 0.50 m and bottom melt from 0.10 m to 0.57 m. The years with the largest amount of surface melt were also years of record minimum ice extent: 2005, 2007, and 2012. The largest amounts of bottom melt have occurred from 2008 to 2013 and are more than double the average from 2000 to 2005, perhaps indicating increased upper ocean warming and foreshadowing greater melt in this region in the future.

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