Arctic sea ice conditions in spring 2009–2013 prior to melt

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Received 13 September 2013; revised 29 October 2013; accepted 30 October 2013; published 19 November 2013.

[1] Measurements from NASA IceBridge airborne surveys in March/April 2009–2013 over the western Arctic Ocean are presented in the context of previous observations to assess changes in the characteristics of the sea ice cover during the last decade, taking into account spatial and temporal limitations in the available data. Following a precipitous drop in the amount and thickness of multiyear (MY) ice in 2007–2008, the characteristics of the ice cover have remained largely consistent through March 2013. The central Arctic continues to be dominated by MY ice with mean and modal thicknesses of 3.2 m and 2.4 m, respectively. The southern Beaufort and Chukchi Sea region is a complex mixture of ~75% first-year ice and 25% MY ice. IceBridge observations indicate that the mean thickness in the Beaufort and Chukchi Seas may have decreased from ~2.5 m to as low as 1.6 m over the 5 year period.
Citation: Richter-Menge, J. A., and S. L. Farrell (2013), Arctic sea ice conditions in spring 2009–2013 prior to melt, *Geophys. Res. Lett.*, *40*, 5888–5893, doi:10.1002/2013GL058011.

1. Introduction

[2] Significant changes in the extent and thickness of the Arctic sea ice cover are widely reported [e.g., *Perovich et al*., 2012]. Key observations include (1) a dramatic reduction in the minimum summer extent [*Stroeve et al*., 2012], (2) a less pronounced reduction in the maximum winter extent [*Cavalieri and Parkinson*, 2012], and (3) a reduction in the relative amount of older, thicker multiyear (MY) ice [*Comiso*, 2012], resulting in a net decrease in volume [*Laxon et al*., 2013]. On 16 September 2012, sea ice extent dropped to 3.41 million km^2, setting a new record summer minimum for the period of near-continuous satellite data available since late 1978.

[3] This paper focuses on the change observed in the composition of the Arctic ice pack, specifically the transition from a predominantly multiyear ice pack (i.e., ice age >1 year) to an increasingly seasonal pack (i.e., ice age ≤ 1 year). We use the new NASA IceBridge sea ice thickness product [*Kurtz et al*., 2013a, 2013b] to evaluate the characteristics of the sea ice cover prior to the summer melt season over the last 5 years. We concentrate our analysis on two regions: (i) the central Arctic Ocean, which remains dominated by multiyear ice, and (ii) the Beaufort and Chukchi Seas, where the ice pack is known to have become more seasonal in nature due to the increased areal extent of summer ice loss. We consider the relative distribution of MY and first-year (FY) ice and the overall mean and modal ice thicknesses in each region. These data extend previous observations to provide a description of the temporal evolution of the ice cover over the last decade and offer insight on the potential linkage between the state of the sea ice cover prior to melt and the summer sea ice minimum in 2013.

2. Data Sets

[4] We use sea ice data collected as part of the NASA Operation IceBridge mission [*Koenig et al*., 2010] during the period 2009–2013. The IceBridge observations are designed to continue a valuable time series of sea ice thickness measurements by bridging the gap between NASA's Ice, Cloud, and Land Elevation Satellite (ICESat), which operated from 2003 to 2009, and ICESat-2, which is scheduled for launch in 2016. The IceBridge sea ice data complement satellite-based estimates of ice thickness derived from CryoSat-2, which was launched in 2010 [*Laxon et al*., 2013], and contemporaneous airborne electromagnetic (EM) ice thickness surveys [*Haas et al*., 2008, 2010].

[5] Since 2009, IceBridge has conducted large-scale airborne surveys of the Arctic Ocean in the March/April time frame. Data from the IceBridge instrument suite are released within 6 months of the field campaign. These data are used to derive sea ice products, including freeboard, thickness, snow depth, surface roughness, and associated uncertainties, at an along-track measurement resolution of 40 m [*Kurtz et al*., 2013a]. Once processed, these data are available to the community via the National Snow and Ice Data Center (NSIDC, http://nsidc.org/ data/idcsi2.html) [*Kurtz et al*., 2012].

[6] Beginning in 2012, the IceBridge program initiated the delivery of a "quick-look" sea ice product, which is also available via NSIDC (http://nsidc.org/data/docs/daac/icebridge/evaluationproducts/sea-ice-freeboard-snowdepth-thickness-quicklook-index.html) [*Kurtz et al*., 2013b]. The quick-look product is a response to community feedback, which indicated a strong interest in developing sea ice products that would be available in a shorter time frame than the standard products (i.e., within weeks of a campaign, versus months). These data have become a standard resource for the Study of Environmental Arctic Change Sea Ice Outlook (http://www.arcus.org/search/seaiceoutlook/data), which provides a summary of community-wide seasonal forecasts of the Arctic summer sea ice minimum extent that are derived using statistical, deterministic, and heuristic methods. The quick-look products have been used to evaluate satellite-based sea ice observations [e.g., *Laxon et al*., 2013] and for data assimilation and model initialization

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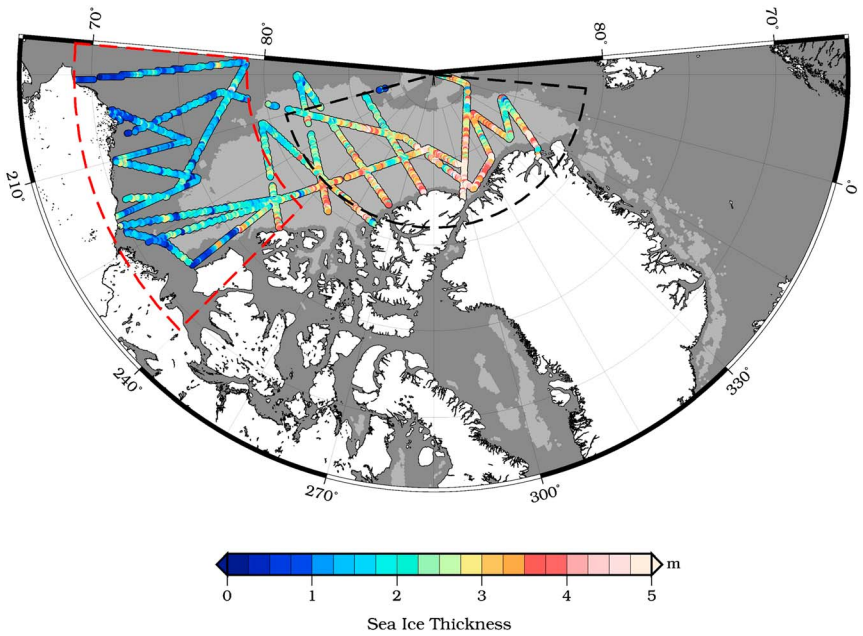

Figure 1. Sea ice thickness in spring 2013, prior to melt, based on the NASA Operation IceBridge quick-look sea ice product. The multiyear ice extent on 26 March 2013 (light grey) is derived from the EUMETSAT OSI SAF sea ice–type product. Regions where changes in the characteristics of the sea ice cover are compared are indicated: the central Arctic Ocean (region A, dashed black line) and the Beaufort-Chukchi Seas (region B, dashed red line).

[e.g., *Lindsay et al.*, 2012]. For this work, we assess the quick-look IceBridge sea ice data products for 2013 (Figure 1) and 2012 (Figure 2d) and the standard products for 2009–2011 (Figures 2a–2c).

[7] The uncertainty associated with the IceBridge ice thickness products has decreased as the mission has evolved due to improvements in both instrumentation and processing techniques [*Kurtz et al.*, 2013a]. Despite the rapid nature of

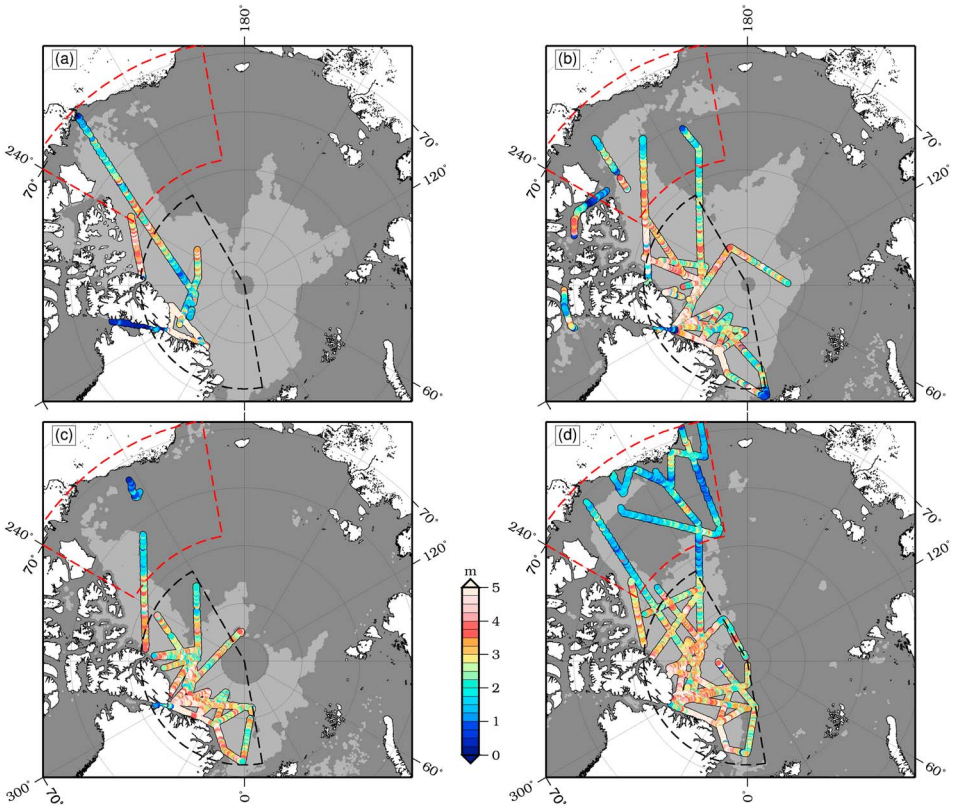

Figure 2. Sea ice thickness in spring (a) 2009, (b) 2010, (c) 2011, and (d) 2012 prior to melt, based on NASA Operation IceBridge sea ice products. Following Figure 1, the light grey region in the background indicates the multiyear ice extent on 26 March of each year based on the EUMETSAT ice-type product. Region A (dashed black line) and region B (dashed red line) are outlined.

Table 1. Summary of Sea Ice Composition and Overall Thickness in Regions A and B, Where an Observation Is Defined as the 2 km Along-Track Arithmetic Average

		Ice Type (%)				
		MY	FY	Number of Observations	Mean ± 1 SD (m)	Mode (m)
2009	Region A	98	2	965	2.90 ± 1.69	2.0
	Region B	31	69	341	2.49 ± 1.01	2.4
2010	Region A	97	3	4595	3.23 ± 1.35	2.4
	Region B	35	65	856	2.57 ± 1.09	2.6
2011	Region A	86	14	6871	3.27 ± 1.32	2.6
	Region B	20	80	259	1.52 ± 0.65	1.8
2012	Region A	86	14	10,670	3.50 ± 1.46	3.0
	Region B	21	79	2152	1.88 ± 0.91	1.2
2013	Region A	88	12	5429	3.04 ± 1.25	2.2
	Region B	23	77	3729	1.60 ± 0.75	1.4
				5 Year Average		
	Region A	91	9	-	3.19 ± 1.41	2.4
	Region B	26	74	-	2.01 ± 0.88	1.9

the quick-look processing, an attempt has been made to preserve data accuracy [*Kurtz et al*., 2013b]. Following *Kurtz et al*. [2013a] in our approach to processing the IceBridge data, we discard any thickness estimates with a freeboard uncertainty greater than 0.1 m. This removed 48%, 37%, 20%, 16%, and 9% of the available ice thickness estimates in 2009, 2010, 2011, 2012, and 2013, respectively. After filtering, the average ice thickness uncertainty was 0.71 m, 0.66 m, 0.66 m, 0.70 m, and 0.59 m for 2009–2013, respectively. The uncertainty associated with the IceBridge thickness estimates is comparable to the errors originally derived in *Giles et al*. [2007] for airborne and satellite-based laser and radar altimeters and consistent with ICESat ice thickness uncertainty [*Kwok and Cunningham*, 2008]. We also apply a 2 km along-track arithmetic averaging scheme to take account of gaps in the data and reduce small-scale along-track variability.

[8] The multiyear ice extent for 26 March 2009–2013 shown in the background of Figures 1 and 2 is derived from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facilities (OSI SAF) sea ice–type product (http://saf.met.no/p/ice/).We chose the 26 March date because the IceBridge program collected observations on this date every year. A review of the OSI SAF maps during this general period indicated little daily variation in the overall composition of the ice pack in the regions of interest.

[9] An effort was made to apply the OSI SAF ice mask to differentiate IceBridge observations of MY and FY ice categories. However, we found inconsistencies between the ice-type product, our visual observations of the ice type, and the IceBridge measurements, particularly where there was a high degree of mixed FY and MY ice (i.e., in region B). We find that the inconsistency is due to the lower resolution of the ice-type product.

3. Results

[10] We compare the annual variability in the characteristics of the sea ice cover in two distinct regions of the Arctic Ocean, delineated by dashed lines in Figures 1 and 2. Region A extends from 210°E to 10°E and 81°N to 90°N. This region encompasses the central Arctic Ocean, which remains dominated by MY ice. Region A includes the oldest [*Maslanik et al*., 2011] and thickest [*Laxon et al*., 2013] remaining ice in the Arctic Ocean, with the thickest ice occurring in the coastal region north of Greenland and the Canadian Arctic Archipelago. Region B extends from 190°E to 240°E and 69°N to 79°N. This region includes the Beaufort Sea and the eastern Chukchi Sea, covering an area that is more transitional in nature with an increasingly seasonal characteristic [*Maslanik et al*., 2011]. Region B tends to be composed of substantial amounts of both FY and MY ice. The southern circulation in the Beaufort Gyre transports the older multiyear ice across the Beaufort and Chukchi Sea region, from the Canada Basin to the Chukchi and Russian sectors. Quantifying the survivability of the ice in region B is crucial for understanding whether the Arctic could be repopulated with multiyear ice, given current climate projections [*Hutchings and Rigor*, 2012].

[11] Table 1 provides a summary of the relative amounts of MY and FY ice in regions A and B, derived using the OSI SAF ice-type delineation. As expected, the relative amount of MY ice in region A (ranging from 98 to 86%) is significantly higher than that in region B (ranging from 35 to 20%). Although there are no major changes in the relative amounts of MY and FY ice in either region over the 5 year period, there is a slight decrease in the percentage of MY ice in both sectors between 2010 and 2011 which persists thereafter. In contrast to the amounts of MY and FY ice, the spatial distribution of the MY ice varies significantly (Figures 1 and 2). In region A, nearly the entire region is covered in MY ice in 2009 and 2010. In 2011, there is a significant area of FY ice north of the Beaufort Sea, extending up to 85°N and as far east as 240°E. In 2012 and 2013, the FY ice in region A is primarily found along the easternmost boundary, north of Fram Strait. In region B, the variation in distribution of the MY ice over the 5 year period is even more pronounced, distinguished largely by the characteristics of a tongue of MY ice that extends from the multiyear pack in the central Arctic into the Beaufort Sea along the Canadian coast. As mentioned earlier and explained in more detail by *Hutchings and Rigor* [2012], this tongue of ice reflects the influence of the Beaufort Gyre on ice motion. The tongue of MY ice is strongly apparent in 2010 and 2012 and weakly apparent in 2009, 2011, and 2013 (Figures 1 and 2). In 2012, there was also comparatively less MY ice in the northeast sector of region B. In sharp contrast to 2012, in 2013, there was a substantial amount of MY ice in the north central Beaufort Sea and the central Canada Basin. In 2013, the observations also indicate an extended area of very thin (~0.5 m) ice in the Chukchi Sea, north of Point Hope, Alaska, which extends eastward toward Barrow (Figure 1). This observation is consistent with the visual observations made by the authors during the 2013 IceBridge flights based out of Alaska. The ice in this area was very grey in color and largely undeformed, consistent with new growth. We believe that this area of thin ice is linked to the large fracture event that occurred during late February 2013 and created an area of open water in this region (http://nsidc.org/arcticseaicenews/2013/03/).

[12] The overall IceBridge-derived mean (±1 standard deviation) and modal thickness estimates for each region

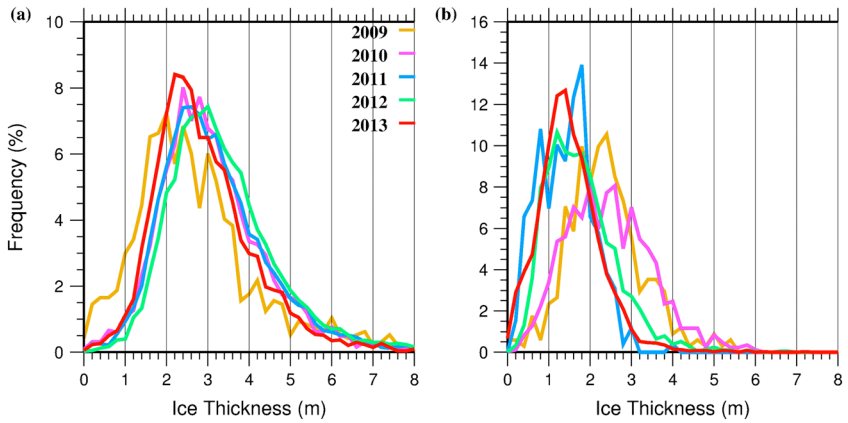

Figure 3. Comparison of sea ice thickness distributions over the 5 year observation period for ice in (a) region A and (b) region B. The bin width is 0.2 m.

are summarized in Table 1. Ice thickness distributions over the 5 year period are presented in Figure 3. As illustrated in Figures 1 and 2 and Table 1 (cf. number of observations), the spatial extent of IceBridge coverage over the western Arctic Ocean has increased since the mission began in 2009. There was a significant increase in the number of observations available in region A after 2009 and in region B after 2011. The latter was the result of a decision to conduct airborne surveys from both Thule Air Force Base, Greenland and Fairbanks, Alaska. In 2013, there was also a deliberate effort to increase coverage in the eastern Beaufort Sea and the Canada Basin.

[13] In region A, which remains dominated by MY ice, variations in the mean and modal thicknesses of the ice cover (Table 1) are consistent with the expected level of interannual variability. The mean and modal thicknesses of the ice in region A over the 5 year observation period are 3.2 m and 2.4 m, respectively. In region B, the mean (2.0 m) and mode (1.9 m) are significantly lower, reflecting the greater mixture of MY and FY ice in this area of transition. It must be acknowledged, however, that the impact of the year-to-year variations in the spatial extent of the IceBridge observations is clearly evident in the ice thickness statistics of region B. In 2009 (Figure 2a) and 2010 (Figure 2b), when the IceBridge observations were collected mainly over MY ice, the mean and modal thicknesses (both ~2.5 m) are relatively high. In 2011 (Figure 2c), the IceBridge observations fall along the periphery of the MY ice zone and over FY ice in the southern Beaufort Sea, and, as a consequence, the mean (~1.5 m) and modal (1.8 m) ice thicknesses both drop significantly. In 2012 and 2013, when spatial sampling over region B increased significantly, the mean (~1.75 m) increased, and the mode (~1.3 m) decreased compared to 2009–2011. The impact of the thin ice observations in the western Chukchi in 2013 can be seen in the ice thickness distribution between 0 and 1 m (Figure 3b, red line). We contend that the 2012 and 2013 IceBridge measurements provide the most representative contemporary estimates of ice thickness in region B, comprising a mixture of MY and FY ice observations.

[14] An April 2009 pan-Arctic airborne electromagnetic (EM) ice thickness survey, reported by *Haas et al*. [2010], provides the most direct comparison with IceBridge observations. The EM survey overlaps in time and includes observations within our regions A and B, albeit at a smaller spatial extent. The accuracy of EM data over level ice is 0.1 m, but the uncertainty may be larger when ridged ice is present [*Haas et al*., 2010]. As such, the modal ice thickness derived from the EM data offers the most accurate resource for comparison. Within region A, EM surveys were conducted in the Lincoln Sea, which is known to contain some of the thickest remaining ice in the Arctic Ocean, and along a line poleward of this region. The highly deformed ice in this region had an EM-derived modal thickness of 4.3 m. The ice along the line toward the North Pole, which was younger and less deformed, had a modal thickness of 2.8 m. In comparison, the 2009 IceBridge observations also show a strong gradient in the ice thickness (Figure 2a), with the thickest ice (≥5 m) occurring along the north coast of Ellesmere Island. However, at 2.0 m, the modal thickness of the IceBridge observations in region A in 2009 is considerably less than the EM-derived results. We note that the IceBridge ice thickness estimates in region A in 2009, northward of the thickest ice along the coast, were the thinnest reported over the 5 year observation period, with long segments of ice 0.5–2 m thick. These are the only observations indicating a significant region of relatively thin ice in the central Arctic Ocean. Within region B, the 2009 comparison with *Haas et al*. [2010] is limited to one EM survey line extending west of Banks Island into a region of mixed FY and MY ice. The modal thickness of the EM-derived FY ice ranged from 2.0 to 2.3 m, and the MY ice ranged from 3.0 to 3.4 m. The IceBridge observations in this same region, which were largely acquired over MY ice, had a modal thickness of 2.4 m.

4. Discussion

[15] The favorable comparison between the 2009 IceBridge results and the airborne EM surveys encourages us to discuss the 2009–2013 IceBridge observations in the context of previous observations to provide a broad look at the changes in the thickness and composition of the sea ice cover over the last decade. Envisat-derived ice thickness anomalies, reported by *Giles et al*. [2008], indicate little change in the overall thickness of the winter sea ice cover from 2002/2003 to 2006/2007. Then, following the record-setting summer melt season of 2007, the average thickness

of the ice cover in the 2007/2008 winter season decreased dramatically, dropping 0.26 m below the average thickness over the previous 6 years. The largest changes in winter 2007/2008 (−0.49 m below the 6 year mean) occurred in the western Arctic. These observations are corroborated by ice thickness estimates from ICESat between 2003 and 2008, which also reveal a dramatic decline in the Arctic-wide ice thickness of about 0.25 m between 2007 and 2008 [*Kwok et al*., 2009]. *Kwok et al*. [2009] also found a >45% decrease in MY ice coverage between 2005 and 2008 and a 0.6 m decrease in its thickness. In contrast, the average midwinter thickness of the seasonal ice remained relatively constant over the period, at ~2 m. Ground and helo-based measurements of late summer ice in the Transpolar Drift region, presented in *Haas et al*. [2008], indicate an overall 1.6 m decrease in modal thickness between 1991 and 2007. The decrease is largely attributed to the replacement of predominantly older MY ice by FY ice in the region. *Haas et al*. [2008] also reported that modal thicknesses at the North Pole "plummeted" from 2.2 m in 2004 to 0.9 m in the summer of 2007. *Maslanik et al*. [2011] reported that the multiyear ice extent in the Arctic Ocean reached a record minimum in March 2008. The loss of MY ice was particularly dramatic in the western regions of the Arctic Ocean, including the Beaufort Sea and the Canada Basin. From 2008 to 2011, Maslanik et al. showed a partial recovery of the total multiyear extent, with the weakest recovery occurring in the Beaufort Sea and the Canada Basin.

[16] The IceBridge observations suggest that since 2009, the relative amount of MY and FY ice in the western Arctic has been maintained into winter 2012/2013, as has the thickness of MY ice in the central basin. Less clear are the changes in the thickness of the seasonal ice that now dominates the Beaufort and Chukchi Seas. A comparison of the mean thickness of the IceBridge observations in March 2012 (1.9 m) and 2013 (1.6 m) with the ICESat estimate of seasonal ice thickness (~2 m) through 2007 suggests a possible decrease in the overall ice thickness in this region. We plan further analyses to confirm the IceBridge results via comparisons to complementary, independent in situ, airborne, and satellite data sets as they become available.

[17] Despite the new record-setting sea ice minimum in summer 2012, we note that the relative composition of FY and MY ice and the mean and modal ice thicknesses in region B did not change significantly between 2012 and 2013. Also recall that, in sharp contrast to conditions in March 2012, in March 2013, there was no well-defined tongue of MY ice in the southern Beaufort Sea. Moreover, there was a region of very thin ice in the Chukchi Sea north of Point Hope in 2013. These ice conditions suggest that the ice cover was well poised for another year of significant loss in summer 2013. In fact, summer 2013 marked a year of significant ice gain in the Beaufort and Chukchi Sea region. The retreat of the ice cover was markedly slow (cf. http://nsidc.org/arcticseaicenews/2013/07/), and the minimum areal extent of 5.1 million km^2, which was reached on 13 September 2013, was ~50% higher than the record minimum set in 2012.

[18] Why is there an apparent disparity between the impact of the 2007 and 2012 record-setting summer ice loss events on the characteristics and thickness of the sea ice cover in the western Arctic? The most likely explanation may be associated with atmospheric forcing conditions, which play a dominant role in determining seasonal conditions [*National Research Council*, 2012]. *Screen et al*. [2011] demonstrated that changes in cyclone occurrence during late spring and early summer over the Arctic Ocean have preconditioning effects on the sea ice cover and therefore exert a strong influence on the amount of sea ice remaining at the end of the summer melt season. More specifically, they find that strengthening of the central Arctic cyclone maximum during the months of May, June, and July helps preserve the ice cover and leads to anomalously high September sea ice extent. This relationship demonstrates the strong links between changes in cyclone activity, atmospheric circulation, ice motion, and cloud cover. Early analysis (e.g., http://nsidc.org/arcticseaicenews/2013/08/) describes storm patterns resulting in low-pressure systems, counterclockwise (cyclonic) winds, and cool conditions during the latter part of July and in August.

[19] In summary, after a precipitous drop in the amount and thickness of multiyear ice in the western Arctic, following the 2007 record-setting ice loss event, the IceBridge data indicate that the overall characteristics of the ice cover have remained largely consistent through March 2013. The central Arctic continues to be dominated by MY ice with mean and modal thicknesses of 3.2 m and 2.4 m, respectively. The southern Beaufort and Chukchi Sea region is a complex mixture of about 75% FY ice and 25% MY ice; however, the spatial distribution of these ice types can change significantly from year to year. Over the 5 year observation period, the IceBridge measurements indicate that the mean thickness in this region may have decreased from ~2.5 m to as low as 1.6 m.

[20] More generally, this analysis demonstrates the achievement of the primary goals of the IceBridge mission to extend the ICESat time series of ice thickness observations and to create a link between ICESat, ICESat-2, and CryoSat-2. Chief among the advantages of IceBridge is the relatively quick access to the data, allowing an assessment of the observations within months of their collection. The analysis also points out the challenge in designing an airborne ice thickness campaign that provides adequate spatial coverage of the dominant regions in the Arctic Basin. In the future, consideration should be given to planning the flight lines based on the timely knowledge of the distribution of FY and MY ice, available from satellite and modeling products. Efforts should also be made to extend the coverage of IceBridge into the eastern Arctic.

[21] **Acknowledgments.** The authors thank the reviewers whose comments were helpful in the revision of this paper. We acknowledge the efforts of the IceBridge team responsible for producing the standard and quick-look IceBridge data products. In particular, we thank the IceBridge Instrument Teams, Science Team, and Project Science Office, as well as the aircraft support crew, for their diligent efforts in gathering and processing these data. This work was supported by NASA grant NNX13AK36G.

[22] The Editor thanks Claire Parkinson and an anonymous reviewer for their assistance in evaluating this paper.

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