Contribution of melt in the Beaufort Sea to the decline in Arctic multiyear sea ice coverage: 1993–2009

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Received 12 July 2010; revised 1 September 2010; accepted 13 September 2010; published 19 October 2010.

[1] For the summers of 1993 through 2009, we estimate the loss of multiyear sea ice (MYI) area in the Beaufort Sea due to melt. Parcels of MYI in April are traced into the Beaufort Sea where they melt as the ice edge retreats. Net loss of area (with fractional MYI coverage >50%) over the 17-year period is ~900 × 10^3 km^2. Three-quarters of that area, ~10% of the area of the Arctic Ocean, was lost after 2000. There is a clear positive trend in the record, with a distinct peak of 213 × 10^3 km^2 in 2008; this is twice the summer outflow at the Fram Strait that year. The net melt area of 490 × 10^3 km^2 between 2005 and 2008 accounts for nearly 32% of the net loss of 1.54 × 10^6 km^2 of Arctic Ocean MYI coverage over the same period. Volume loss, for the years with ICESat thickness (2004–2009), is highest at 473 km^3 in 2008 followed by 320 km^3 in 2007. Net loss in MYI volume for the six summers is ~1400 km^3. This is ~20% of the loss in MYI volume of 6300 km^3 during 2004–2008. This adds to the freshwater content of the Arctic Ocean and locally to the freshening of the Beaufort Gyre. **Citation:** Kwok, R., and G. F. Cunningham (2010), Contribution of melt in the Beaufort Sea to the decline in Arctic multiyear sea ice coverage: 1993–2009, *Geophys. Res. Lett.*, *37*, L20501, doi:10.1029/2010GL044678.

1. Introduction

[2] After the onset of fall freeze-up in late September, the multiyear sea ice (MYI – ice that survived more than a summer) of the Arctic Ocean repeats its annual cycle of gradual decline in coverage that is explained almost entirely by the large wind-driven export through the Fram Strait. On average, ~10% of the Arctic Ocean area is lost to export every year [*Kwok*, 2009]. Over 80% of that area is exported in the winter (Oct–May); the sea ice outflow is typically lower during the four summer months (Jun–Sep) when sea-level pressure gradients across the strait are weaker. It is sometimes assumed that the loss of MYI area due to melt within the Arctic is relatively small, although in recent years the contribution of this component to the annual cycle of MYI coverage has received more attention as the ice cover thins. Nonetheless, the magnitude of these melt areas has yet to be quantified.

[3] Attributions of the loss of MYI have become more compelling in view of the alarming changes seen in the Arctic Ocean ice cover in recent years. Over the passive microwave satellite record, negative trends of ~10% per decade in the Arctic Ocean MYI cover was estimated by *Comiso* [2002]. This rate of decline can be contrasted to the more moderate rate of −4% per decade in the total sea ice extent of the Northern Hemisphere [*Comiso et al.*, 2008]. Recent analysis of the 10-year MYI record from QuikSCAT [*Kwok et al.*, 2009] shows an astonishing loss of 42% of the winter MYI area (or 1.54 × 10^6 km^2) in the years between 2005 and 2008. The winter MYI coverage in 2008 stands at ~34% of the Arctic Ocean compared to that of ~70% three decades ago.

[4] Could an increase in ice export alone explain the net decrease of 42% in MYI area in three years? *Ogi et al.* [2010] have shown that recent atmospheric circulation patterns are favorable to increased advection of sea ice towards the Fram Strait. Yet, *Kwok* [2009] showed that the trend of Fram Strait area export over a 29-year record to be negligible; the increased wind forcing was accompanied by a decrease in ice concentration at the Strait. Thus, the question remains as to whether the melt of MYI within the Arctic Ocean could in part account for the observed loss in MYI coverage. Evidence of MYI melt during the summer can be seen in the winter RADARSAT image, and winter and fall QuikSCAT analyses of MYI coverage in Figure 1. The fragmented MYI in the Beaufort Sea (white box) prior to the onset of melt (on April 30, 2008 (Figure 1b)) is no longer present in the MYI coverage in the late fall after freeze-up (on November 30, 2008 (Figure 1c)). This suggests a loss of those areas within the box due to melt. However, direct estimates of MYI coverage during the summer are not reliable, necessitating a different approach in estimating the melt area of MYI.

[5] Our present note examines a 17-year time series (1993–2009) of the loss of MYI area in the Beaufort Sea using products from the following satellite data sets: ERS-1/2, QuikSCAT, SSM/I, and ICESat. Because of the difficulty in identifying sea ice types in the summer, our approach is to use ice motion to track parcels of MYI in April into the Beaufort Sea where they melt as the ice edge retreats. Over the entire record, we compare the annual and cumulative melt areas with the ice export areas at the Fram Strait. Net volume of freshwater introduced into the ocean is computed for the years when ICESat thickness estimates are available.

2. Data Description and Approach

[6] The datasets used in this work include: 1) MYI coverage on April-1 from the ERS (1993–1999) and QuikSCAT (1999–2009) scatterometers; 2) Daily fields of sea ice motion and ice concentration from satellite passive microwave data (1993–2009); and 3) winter ice thickness from ICESat (2004–2009) [*Kwok et al.*, 2009]. Estimation and assessment of the spatial distribution of MYI coverage from scatterometer fields are described by *Kwok* [2004]. Satellite passive microwave ice concentrations from the Bootstrap algorithm are used here. Passive microwave ice motion fields are those described by *Kwok et al.* [1998] and *Kwok* [2008]. For these

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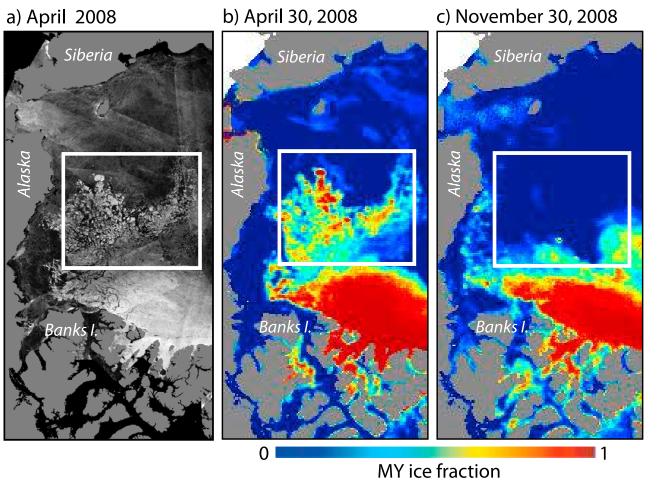

Figure 1. (a) SAR image mosaic of the Western Arctic in April 2008 from RADARSAT. QuikSCAT-derived multiyear sea ice coverage map of the Arctic Ocean (b) before (April 30) and (c) after the summer of 2008 (November 30). The large area of fragmented MYI pack in the Beaufort Sea within the white box disappeared from the map after the summer minimum in ice coverage. RADARSAT images of the Arctic Ocean are not available after mid-2008. (RADARSAT Images © CSA 2010).

fields, uncertainty in the daily motion vectors is ~5 km/day when assessed with buoy drift. However, these estimates are expected to be less reliable near the ice edge and we take the uncertainty to be 7 km/day.

2.1. Estimation of MYI Melt Area (A_{MYI}^{melt})

[7] To estimate the melt of MYI ice during the summer, the spatial distribution of MYI coverage within the ice cover is needed. Since the analysis of MYI coverage in QuikSCAT and ERS backscatter fields becomes unreliable after the onset of melt, our approach is to trace the location of individual pixels (12.5 km × 12.5 km) of sea ice in the scatterometer analyses from April-1, prior to melt onset, into the summer using satellite passive microwave ice motion. The following two steps are repeated in the estimation of melt area: 1) Propagate the center location of individual pixels in the scatterometer fields using daily fields of ice motion; and, 2) Calculate the MYI area in those pixels that are located, after propagation, outside the daily ice edge as defined by the 15% ice concentration isopleth. Individual pixels are treated as Lagrangian elements with no convergence or divergence, and each element assumes its own unique drift trajectory through the late spring and into summer. Local changes in MYI fraction due to ice deformation are not accounted for, but since no MYI is created during the spring or summer, the MYI area in April is conserved, save for melt, throughout the spring and summer seasons. Here, MYI area is the sum of the area (weighted by MYI fraction) of those pixels with >50% MYI fraction. We use this threshold to reduce the errors in melt-area calculations due to uncertainties in the scatterometer analysis of MYI fraction. Thus, the melt-areas are conservative estimates.

[8] Variability in A_{MYI}^{melt} due to errors in the passive microwave ice motion fields and the daily propagation process are assessed with Monte-Carlo simulations. Under each simulation, uncorrelated normally-distributed vector noise fields are added to the set of daily motion fields used in our calculations to obtain a distinct estimate of A_{MYI}^{melt}. For each summer, we perform 100 realizations of the above simulation to assess the variability in A_{MY}^{melt} calculated using our approach. The results are discussed in the next section. Individual noise vectors, as discussed above, have an expected magnitude of 7 km/day.

2.2. Estimation of Melt Volume

[9] Gridded fields (12.5 km × 12.5 km) of ice thickness from the winter ICESat campaigns between 2004 and 2009 [*Kwok et al.*, 2009] are used in this calculation. Since an ice element that melts in the summer can be traced backed to its original location on April-1, we can calculate the approximate ice volume of that pixel in the co-registered QuikSCAT and winter ICESat fields. Thus, the melt volume here is of ice volume on April-1. The ice thickness by this time of the season is typically near its peak in the seasonal cycle and therefore the best estimate of the melt volume if that area was lost during the summer. We also note that the melt volume from the surface/bottom of MYI areas that survive the summer is not considered here.

3. Annual Loss of MYI Area in the Beaufort Sea (1993–2009)

[10] A_{MYI}^{melt} is estimated within the region of the Arctic Ocean outlined by the red polygon in Figure 2a. The annual A_{MYI}^{melt} (with >50% coverage) over the 17-year record is shown in Figure 2b. Figure 2c shows the progression of A_{MYI}^{melt} from June-1 to September-30 (after ice minimum) obtained using our approach. For each of the 17 summers, we show: 1) the daily and cumulative melt areas, and their uncertainties; 2) an associated map that shows the ice coverage at summer minimum (in gray), the melt areas, and the MYI fraction within those melt areas; and 3) for comparison, the corresponding cumulative summer ice area export at the Fram Strait for the same period. In this section, we first address the uncertainties in the estimates before discussing the seasonal and interannual variability of A_{MYI}^{melt}.

[11] Uncertainties in daily and cumulative melt areas are shown as green and blue bands around their respective estimates. The bounds of the colored bands are the daily extremes (minimum and maximum) in A_{MYI}^{melt} obtained from the 100 Monte-Carlo simulations described previously. As expected, the estimates of daily A_{MYI}^{melt} are quite variable (noisy) due the uncertainties in ice motion but the cumulative estimates are better bounded as the net area (i.e., signal) increases. The size

Figure 2. Loss of multiyear sea ice area in the Beaufort Sea between June-1 and September-30 (1993–2009). (a) Box within Arctic Ocean map shows region where melt is computed. (b) 17-year time series of annual melt areas. (c) For each summer, line plots show the daily (top) and cumulative (bottom) melt areas. Attached maps show the ice coverage (>15% concentration) at summer minimum (in gray) and the location of ice melt. Colors within the melt areas represent the multiyear sea ice fraction. The cumulative ice area export at the Fram Strait (in red) for the same period is shown for comparison. Uncertainties in daily and cumulative melt areas are in green and blue.

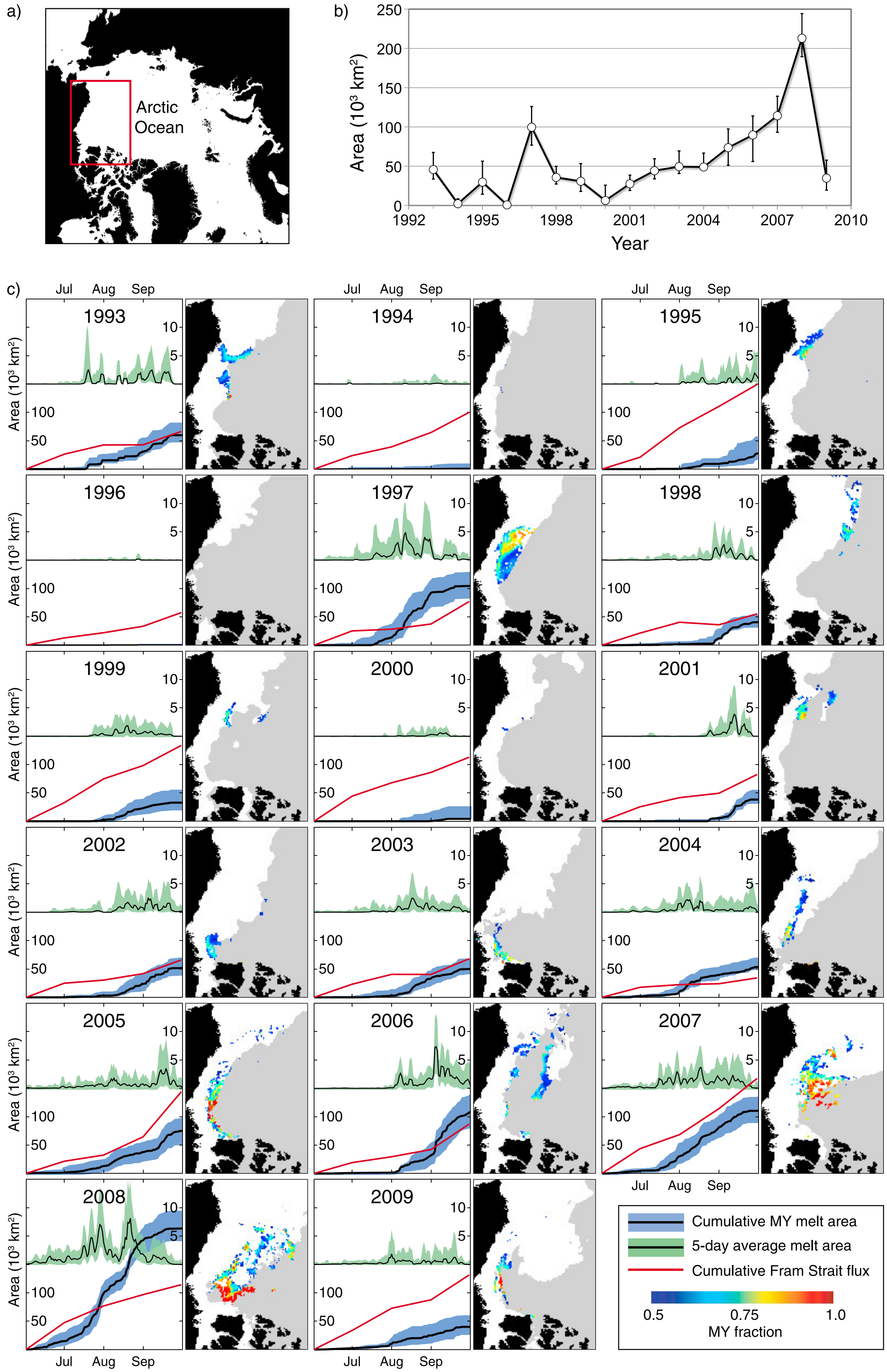
a)
Arctic
Ocean
b)
Area (10³ km²)
Year
250
200
150
100
50
0
1992
1995
1998
2001
2004
2007
2010
c)
Jul
Aug
Sep
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
10
5
100
50
Cumulative MY melt area
5-day average melt area
Cumulative Fram Strait flux
0.5
0.75
1.0
MY fraction

Figure 2

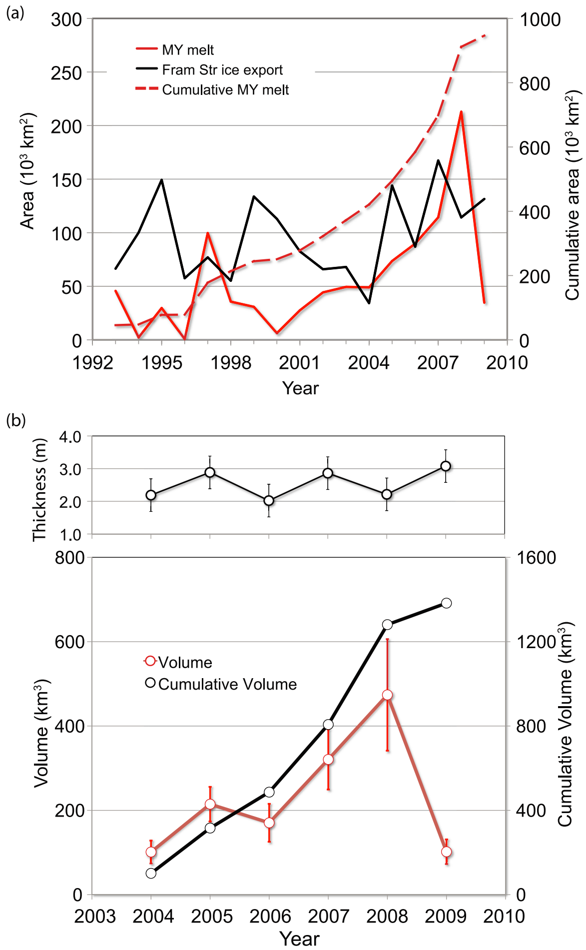

Figure 3. (a) Comparison of loss of multiyear sea ice in the Beaufort Sea (annual and cumulative) with summer Fram Strait ice area export (1993–2009). (b) Estimates of annual and cumulative volume loss of multiyear sea ice between 2004 and 2009.

of the daily uncertainties seems to depend on the geometry of the MYI cover exposed at the ice edge. When the MYI pack is consolidated, as in 1997, the daily uncertainties are higher because small perturbations in ice motion cause larger changes in the melt area estimates. In contrast, the variability is lower when the MYI pack is fragmented. The contribution of the uncertainties in daily A_{MYI}^{melt} estimates to the uncertainties in net melt area at the end of summer is variable, but on average ~25 × 10^3 km^2. Except for the summers when the melt areas are almost negligible (1994, 1996, and 2000), that is between ~8 to 48% of the net melt area.

[12] Seasonally, excluding the summer of 2008, there is generally no melt activity until mid- to late-July. This is followed by a gradual build up in A_{MYI}^{melt} towards the end of the summer. In 2008, the ice cover retreated earlier and farther from the coast than other years. The attached map for the summer of 2008 (in Figure 2c) shows that the fragmented MYI within the white box in Figure 1a was indeed lost to melt. Similarly, the MYI area lost in 2007 was also fragmented compared to 1997, highlighting perhaps the consequence and importance of lateral melt during the summer if the consolidated MYI cover was broken up during winter storms before or during the melt season.

[13] The behavior of the 17-year record of net area of summer melt (in Figure 2b) shows that it cannot be adequately described by the usual first (mean) and second (standard deviation) moments in statistics. Prior to 2001, there is an extreme in net A_{MYI}^{melt} of 110 × 10^3 km^2 in 1997 when the other years were all less than half that value. After 2000, the time series is characterized by a near monotonic increase to a distinct peak in 2008 of 213 × 10^3 km^2 – twice that of any other year on record – followed by a steep decrease in 2009. The A_{MYI}^{melt} in 2007 (at 114 × 10^3 km^2) is only second highest, during this summer of record minimum in sea ice coverage in the Arctic Ocean. Even though the ice edge at minimum is fairly far north in 2009 (as seen in the Figure 2c), the MYI coverage in the Beaufort Sea was particularly low that summer as the large melt event in 2008 had removed most of the MYI in the Beaufort Sea, and that MYI coverage was not replenished via advection by the circulation pattern prior to that summer. Additionally, that tongue of MYI just west of the Canadian Arctic Archipelago seems to have survived the summer, whereas in 2007 and 2008 that distinct tongue of MYI was lost to melt by the end of summer.

[14] Figure 2c also compares the MYI melt area with summer ice export at the Fram Strait. We note here that the area export estimates include MYI and seasonal ice, and we do not have an effective way of separating the total area into their relative contributions at this time, thus it should be noted that only a fraction of that area is MYI. During late summer, the MYI fraction is expected to be high after most of the first-year ice has melted away. These comparisons show that the loss of MYI area in the Beaufort Sea is higher than the summer ice area flux at the Fram Strait in four years of the record (1997, 2004, 2006, and 2008). But most remarkably, the MYI melt area in 2008 (213 × 10^3 km^2) is nearly twice that of the summer Fram Strait area export (114 × 10^3 km^2). Expected uncertainties in the summer ice export are ~20–30 × 10^3 km^2.

4. Net Melt Area, Volume, and Depletion of Arctic MYI Coverage (1993–2009)

[15] Clearly, the loss of MYI area associated with melt in the Beaufort Sea, especially after 2000, contributes directly to the depletion of Arctic MYI coverage. Figure 3a compares the cumulative and annual loss of MYI area in the Beaufort Sea during summer with the net Fram Strait ice area export over the 17-year record (1993–2009). Over the record, the total loss of MYI area in the Beaufort Sea due to melt is 947 × 10^3 km^2. Approximately 490 × 10^3 km^2 of that area was lost in the four summers between 2005 and 2008. This is nearly 32% of the net loss of 1.54 × 10^6 km^2 in winter MYI coverage of the Arctic Ocean for the same period [*Kwok et al.*, 2009]. Overall, melt in the Beaufort Sea – associated with the poleward retreat of the summer ice edge, especially in the latter half of the 17-year record – has contributed to the decline of Arctic MYI coverage.

[16] Here, we estimate the relative contribution of summer ice export at the Fram Strait to the depletion of MYI coverage. Over the 17-year record, the export of sea ice area during the summer (June–September) has a mean (S.D) of 97(38) × 10^3 km^2, with an overall trend of 2.2 × 10^3 km^2/yr and a higher trend of 13.6 × 10^3 km^2/yr toward the end of the record. Using the higher trend, the increase in summer export over the four years between 2005 and 2008 is ~50 × 10^3 km^2,

a fairly small contribution to the total loss of 1.54×10^6 km^2. Even though there is no significant trend in the annual Fram Strait ice export in the 29-year time series [*Kwok*, 2009], the net anomalous outflow for the 2005–2008 period is only ~300×10^3 km^2 relative to the record mean. As the export estimates are of total ice area (i.e., MYI and first-year), this outflow at the Fram Strait could contribute up to 20% of the total MYI loss. Taken together, the Beaufort melt and summer export at the Fram Strait could explain only ~45% of the MYI loss between 2005 and 2008.

[17] The volume of ice from the melt areas is estimated using the procedure described earlier. Figure 3b shows the mean ICESat thickness of the MYI areas (with >50% coverage), the melt volume, and the cumulative volume for the period between 2004 and 2009. Volume loss due to areal melt in the Beaufort is highest, at 473 km^3, in 2008, followed by 320 km^3 in 2007. These losses are not insignificant. For comparison, they are ~21% and 15% of the mean annual volume flux at the Fram Strait of 2200 km^3/yr (between 1991 and 1999).

[18] Net loss of MYI volume in the Beaufort Sea for the six ICESat years, accounted for by our procedure, is ~1400 km^3. This is ~20% of the net loss in MYI volume of 6300 km^3 during the 2004–2008 time period [*Kwok et al.*, 2009].

5. Conclusions

[19] This note examines a 17-year record (1993–2009) of loss in MYI coverage in the Beaufort Sea during the summer and its contribution to the recent decline in winter MYI coverage in the Arctic Ocean. These results are contrasted with summer ice area export at the Fram Strait. For the years (2004–2009) when we have ICESat thickness estimates, the ice volume loss is computed.

[20] Prior to 2001, there is an extreme in net MYI melt of 110×10^3 km^2 in 1997 while the other years were all less than half that value. After 2000, the melt-area record is characterized by a near-monotonic rise that peaked at 213×10^3 km^2 in 2008 followed by a sharp drop-off in 2009. The MYI melt area in 2007, at 114×10^3 km^2, is only second highest during this summer of record minimum in Arctic Ocean sea ice coverage.

[21] The net loss of MYI area over the entire record is 947×10^3 km^2. The loss of 490×10^3 km^2 between 2005 and 2008 is nearly 32% of the net loss of 1.54×10^6 km^2 in winter Arctic Ocean MYI coverage over those three years. For the six ICESat years, loss of MYI volume accounted for by our procedure is ~1400 km^3. This is ~20% of the net loss in MYI volume of 6300 km^3 during the 2004–2008 period [*Kwok et al.*, 2009]. In summary, the melt of MYI in the Beaufort Sea accounts for 32% and 20% of the area and volume losses of MYI during the ICESat period. This adds to the freshwater content and contributes to the freshening of the Beaufort Gyre [*Proshutinsky et al.*, 2009].

[22] The MYI melt in the Beaufort Sea, together with the net anomalous area outflow at the Fram Strait (<300×10^3 km^2) explains only 52% of the overall MYI loss between 2005 and 2008. How can we account for the remaining 48% of the MYI area loss during this period? An obvious approach is to use our present procedure to examine melt in other parts of the Arctic. It would be worthwhile to estimate the MYI melt associated with the remarkable poleward retreat of the summer ice edge in the Siberian sector of the Arctic Ocean. Reduced survival of seasonal ice, as noted by *Kwok et al.* [2009], is certainly important. Outflow of MYI at other passages also contribute to loss in coverage. The anomalous MYI outflow (> mean) at Nares Strait though large over the same period, at ~40×10^3 km^2, is a relatively small contribution [*Kwok et al.*, 2010]. One of the difficulties in accounting for all of the MYI areas is the uncertainty in the contribution of ice dynamics (i.e., convergence) to the decline in MYI coverage. The thinner MYI cover is more deformable (in terms of ridging). This contribution would be dependent on the seasonal variability in ice circulation. Convergence, especially when the ice is pushed against the northern Greenland coast and Ellesmere Island, could cause significant reduction in area that could be misconstrued as loss due to melt or export. Hence, these considerations are important when interpreting overall decline in MYI coverage. The coarseness of available observations may not allow us to resolve the role of ice dynamics.

[23] **Acknowledgments.** The SMMR and SSM/I brightness temperature and ice concentration fields are provided by World Data Center A for Glaciology/National Snow and Ice Data Center, University of Colorado, Boulder, CO. The QuikSCAT data are provided by the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory, Pasadena, CA. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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