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Rapid reduction of Arctic perennial sea ice

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[1] The extent of Arctic perennial sea ice, the year-round ice cover, was significantly reduced between March 2005 and March 2007 by 1.08×10^6 km^2, a 23% loss from 4.69×10^6 km^2 to 3.61×10^6 km^2, as observed by the QuikSCAT/SeaWinds satellite scatterometer (QSCAT). Moreover, the buoy-based Drift-Age Model (DM) provided long-term trends in Arctic sea-ice age since the 1950s. Perennial-ice extent loss in March within the DM domain was noticeable after the 1960s, and the loss became more rapid in the 2000s when QSCAT observations were available to verify the model results. QSCAT data also revealed mechanisms contributing to the perennial-ice extent loss: ice compression toward the western Arctic, ice loading into the Transpolar Drift (TD) together with an acceleration of the TD carrying excessive ice out of Fram Strait, and ice export to Baffin Bay. Dynamic and thermodynamic effects appear to be combining to expedite the loss of perennial sea ice. **Citation:** Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colón, J. W. Weatherly, and G. Neumann (2007), Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, *34*, L19504, doi:10.1029/2007GL031138.

1. Introduction

[2] In this decade, Arctic sea ice extent has significantly reduced in summer [*Comiso*, 2002, 2006; *Sturm et al.*, 2003; *Rigor and Wallace*, 2004; *Francis et al.*, 2005; *Nghiem and Neumann*, 2007; *Stroeve et al.*, 2007]. Within the total ice extent, Arctic sea ice consists of two major ice classes: perennial (multi-year) and seasonal (first-year) sea ice. Each of these ice classes has distinctive physical characteristics in thickness, albedo, salinity, brine inclusion, and roughness [*Weeks and Ackley*, 1982]. In terms of total sea ice mass, the old and thick perennial ice dominated the younger and thinner seasonal ice that melted away in summer. Most notably, perennial ice is more likely to survive the summer melt season. Changes in perennial ice are therefore crucial to the mass balance of Arctic sea ice.

2. Approach

[3] Global backscatter data have been acquired by the U.S. National Aeronautics and Space Administration (NASA) SeaWinds scatterometer aboard the QuikSCAT satellite (QSCAT) since its launch in June 1999, with an Arctic-wide coverage two times per day. An algorithm to detect and map Arctic sea ice from QSCAT data was developed and applied to measure the loss of perennial sea ice in 2005 [*Nghiem et al.*, 2006a]. Furthermore, lakes and other inland water bodies are eliminated to avoid biases in the results for Arctic sea ice. Once the sea ice cover is mapped, perennial and seasonal ice can be distinguished based on their distinctive backscatter signatures [*Nghiem et al.*, 2006a]. In an area where there is a mixture of seasonal and perennial ice, the overlap between their backscatter signatures is used to identify a mixed sea ice class. When seasonal ice is strongly compressed, it can be significantly thickened and roughened by rafting and ridging, and also desalinated by brine drainage. These characteristics make the deformed seasonal ice similar to perennial ice in physical properties and backscatter signature, and this ice type is included in the class of mixed ice. QSCAT results were verified with field observations and sea ice charts from the National Ice Center (NIC) [*Nghiem et al.*, 2006a].

[4] While satellite scatterometer data have been used to closely monitor winter perennial and seasonal sea ice distribution on a daily basis in recent years (1999-present), the DM [*Rigor and Wallace*, 2004] provides a half-century estimate of Arctic sea ice age distribution to determine the long-term trend since the 1950s. To calculate the age of sea ice, the DM tracks a grid of points (ice parcels) as they move about the Arctic Ocean. This model defines new, first year sea ice in areas of open water in September (the month of the climatological annual minimum in sea ice extent), and advects these ice parcels using the monthly gridded fields of ice motion based on buoy and ice-camp data. If these drifting parcels lie within the limit of the ice edge in September the following year, they are said to have survived the summer melt, and these parcels are marked as one-year older. The process is repeated for each year from September 1955 to April 2007. Because of the limited number of buoys, variations in sea ice motion may not be adequately captured in some regions, resulting in uncertainties in the final results.

[5] Analysts from the NIC derive sea ice charts primarily from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS), the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS), and satellite synthetic aperture radars (SAR) such as the Canadian RADARSAT SAR and the European Envisat SAR. Such ice charts are used to compare with the new QSCAT results. In addition to buoy data used in the DM, location data from Arctic ice mass balance (IMB) buoys, equipped with sensors to measure snow and ice while the buoy locations

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Table 1. Mean Values and Standard Deviations of the Extents of Different Sea Ice Classes for the Month of March in 2006–2007 for Entire Arctic Ocean[a]

Year	Perennial Ice, million km^2	Seasonal Ice, million km^2	Mixed Ice, million km^2	Total Ice Extent, million km^2
2005	4.69 ± 0.10	6.28 ± 0.12	2.98 ± 0.14	14.24 ± 0.13
2006	4.23 ± 0.09	6.54 ± 0.12	2.99 ± 0.10	13.99 ± 0.16
2007	3.61 ± 0.13	7.01 ± 0.22	3.23 ± 0.20	14.15 ± 0.09

[a]Values include ocean regions outside the DM domain. For mixed ice, only about 32% of the ice extent was inside the DM domain.

are tracked, supply further measurements to cross validate the satellite results.

3. Results

[6] In view of Arctic sea ice mass balance, the distribution of perennial and seasonal sea ice in March is particularly important. Sea ice distribution in March represents the transitional condition from winter to spring as the solar heat flux starts to increase and the melt process commences and continues into summer. Besides differences in ice thickness, these major ice classes partition solar energy differently, with the perennial ice having a larger albedo and also transmitting less solar radiation to the ocean [*Perovich et al.*, 2002]. The shift from perennial to seasonal ice thus impacts the ice mass balance and the ice-albedo feedback mechanism.

[7] Results from QSCAT averaged over March show a reduction in perennial ice extent from 4.69×10^6 km^2 in March 2005 to 3.61×10^6 km^2 in March 2007 (Table 1). This is a decrease of 1.08×10^6 km^2, about the area of California and Texas combined. A large reduction of 0.62×10^6 km^2 between March 2006 and 2007 followed the previous year's loss of 0.46×10^6 km^2, resulting in a 23% loss in perennial ice extent in just two years. While the perennial ice decreased, seasonal ice extent increased from 6.28×10^6 km^2 in March 2005 to 7.01×10^6 km^2 in March 2007 (Table 1), indicating that most of the extent loss from perennial ice was replaced by seasonal ice. Mixed ice extent, the least among the different ice classes, had practically no change between 2005 and 2006 and had an increase between 2006 and 2007 that was about one standard deviation of QSCAT ice observations. As a result, the total coverage of all sea ice classes was relatively stable around the average of 14.12×10^6 km^2 over the three years (March 2005–2007). This is different from the change in total ice extent observed by satellite radiometer data between 2005 and 2006 [*Comiso*, 2006].

[8] In Figure 1, QSCAT results for Arctic perennial ice are compared with ice-age distribution (one year or older) derived from the DM for March 2005–2007. QSCAT ice maps in 2004 and earlier were published elsewhere [*Nghiem and Neumann*, 2007]. The QSCAT images show a large reduction in perennial ice extent between 2006 and 2007, which followed the significant perennial ice decrease between 2005 and 2006 when most of perennial ice occupied the West Arctic Ocean (west longitudes between 0–180°) as previously reported [*Nghiem et al.*, 2006a]. In 2007, perennial ice continued to be pushed to the West Arctic Ocean and reduced over a large area in the Chukchi Sea and the Beaufort Sea. This comparison also illustrates the complement between QSCAT and DM results. While QSCAT can measure perennial ice extent with better spatial and temporal resolution, the DM can estimate the distribution of second-year and older ice, revealing a large reduction in its total extent between 2005 and 2007 (Figure 1).

[9] In March 2005, QSCAT and DM maps (top panels of Figure 1) agreed overall that the perennial ice extent was significantly larger than in 2006 and 2007, clearly showing the extensive loss of perennial ice. For March 2006, the QSCAT and DM maps (middle panels of Figure 1) were mostly consistent in the distribution of perennial ice in the West Arctic and seasonal ice in the East Arctic (east longitudes between 0–180°). However, detailed features in the sea ice distribution showed that QSCAT and DM results had local differences. For instance, the boundary of DM perennial ice (middle right panel in Figure 1) reached closer to the North Pole, there were areas of QSCAT perennial ice outside the DM contour in the Beaufort Sea, and there was more old ice in the DM map to the west of the Canadian Banks Island compared to the QSCAT observations (middle left panel in Figure 1).

[10] For March 2007, both QSCAT and DM sea ice maps (bottom two panels in Figure 1) agreed that the perennial ice was confined mostly in the West Arctic Ocean while the East Arctic Ocean was dominated by seasonal ice. However, there were regional differences between QSCAT and DM results. In the Beaufort Sea, perennial sea ice seen in the DM map (bottom right panel in Figure 1) consisted of more mixed ice in the QSCAT map (bottom left panel in Figure 1). A QSCAT animation (Animation 1) indicates that active ice dynamics broke up the original perennial ice to create the mixed ice by cycles of convergence and divergence in the Beaufort Sea. Such ice dynamic changes were averaged out in the monthly ice motion vector field interpolated from a small number of buoys in the DM result, which could not capture the change observed by QSCAT having significantly better spatial and temporal resolution. Another difference in 2007 can be seen in the ocean region north of Franz Josef Land and Spitsbergen where QSCAT showed that the perennial ice had moved further north compared to the DM result, which was defaulted to a climatological drift due to a lack of buoys in this region. The differences resulted in a smaller total extent of perennial ice measured by QSCAT compared to that estimated by the DM in March 2007.

[11] Some perennial ice was inside the extent of mixed ice by definition. To estimate how much perennial ice change occurred in mixed ice, its extent was calculated within the DM domain, which excluded the Bering Sea, the Canadian Arctic archipelago, Baffin Bay, the sea ice portion at lower latitudes in the Greenland Sea, and other peripheral ocean areas. Outside the DM domain was 68% mixed ice, consisted of seasonal ice and perennial-like ice (compressed and deformed first-year ice) or true perennial ice that was exported (Greenland Sea and Baffin Bay). In the DM domain, the extent of mixed ice was stable around an average value of $0.97 \times 10^6 \pm 0.09$ km^2. The change of mixed ice extent between March 2006 and March 2007 was 0.16×10^6 km^2, only part of which was truly perennial ice. Such change is within the variability of QSCAT observations (Table 1).

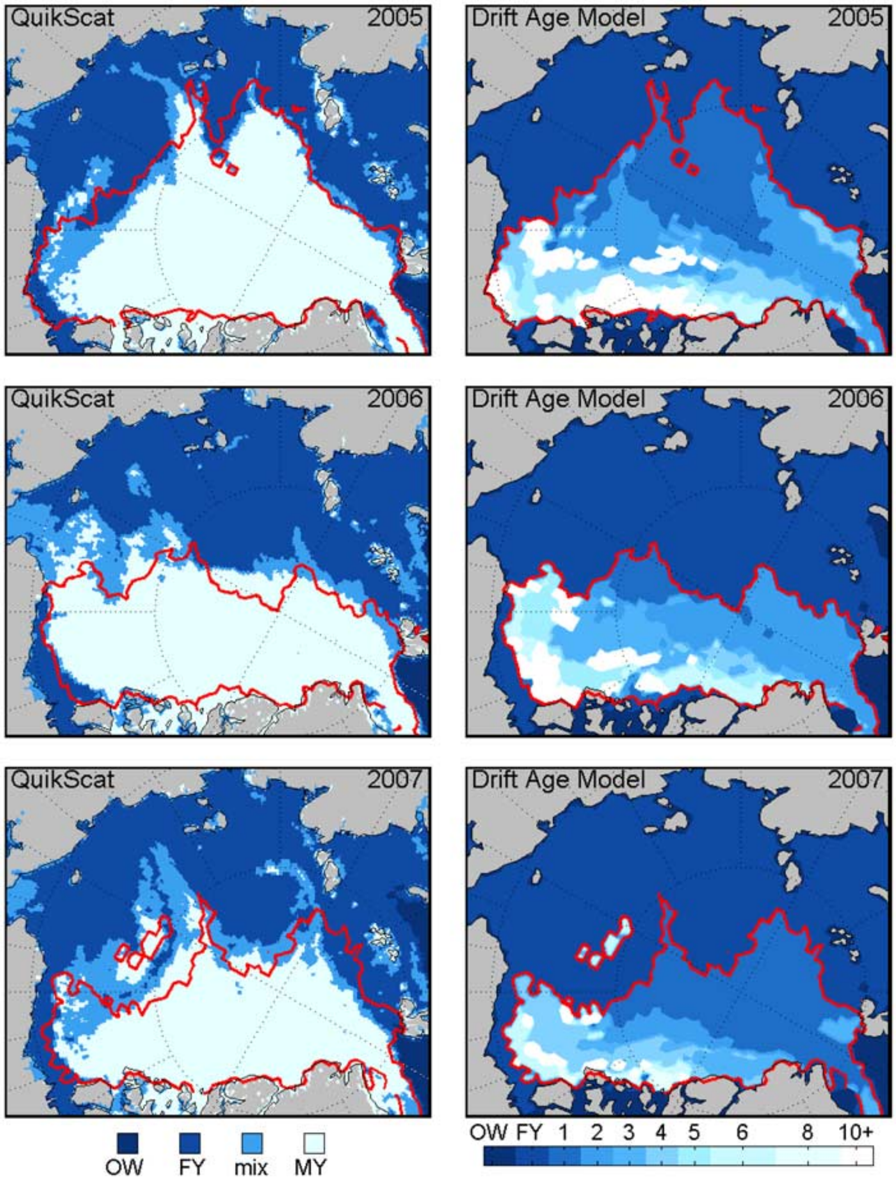

Figure 1. Comparison of (left) QSCAT observations (on spring equinox) and (right) DM estimates (average over March) of perennial sea ice distribution. The red line represents the boundary of perennial ice from the DM (ice age older than 1 year). OW stands for ice-free open water, FY for first-year or seasonal ice, mix for mixed ice, MY for multi-year or perennial ice, and the scale 1–10 for ice age.

[12] The 2007 QSCAT ice distribution compares fairly well with the NIC ice contours in Figure 2 regarding the overall features of the dominant sea ice pack in the West Arctic Ocean. The NIC contour of perennial and mixed ice, containing 60% or more of perennial ice, includes the major features of perennial and mixed ice extent observed by QSCAT. However, results from the NIC ice chart do not distinguish well between mixed ice and perennial ice, such as in the elongated arm of apparently perennial ice in the Beaufort Sea (Figure 2). This is due to the similar signatures of perennial ice and mixed ice, especially when it contains thick or deformed first-year ice, in optical imagery [*Riggs et al.*, 1999] and in C-band SAR data [*Nghiem and Bertoia*, 2001]. Only 4.16% of QSCAT data in all data sources were used in making the NIC Arctic ice chart, which can be considered as an independent verification of the QSCAT result.

[13] Figure 3 presents a time series area of perennial sea ice extent in the DM domain observed by QSCAT in 2000–2007 and estimated by the DM in 1957–2007. The trend in DM estimates (for the month of March) and QSCAT observations (on spring equinox in March) compare well for the perennial ice extent over the overlapping time period, both showing the lowest value in 2007. Most importantly, DM can provide long-term results to identify the multi-decadal trends in Arctic perennial ice change. In the 1950s and 1960s, there was no discernible trend. Between 1970 and 2000, the loss in perennial ice extent was significant, with a rate of decrease estimated at about 0.5×10^6 km^2 per decade. In this decade, perennial ice

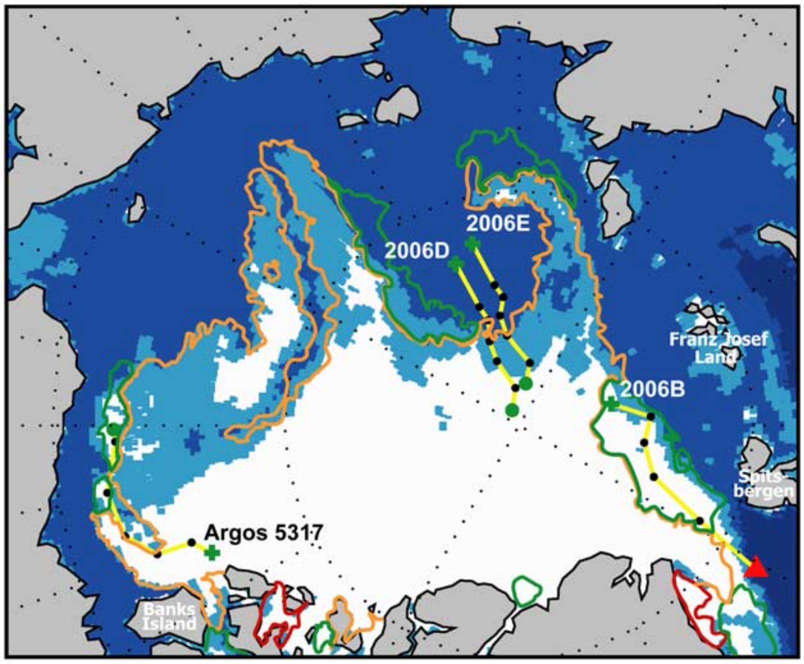

Figure 2. QSCAT map of sea ice classes for 21 March 2007 (same as the bottom left panel of Figure 1) together with NIC sea ice contours, obtained from a sea-ice chart prepared primarily with optical and SAR data collected in the period of 24–27 March 2007. The NIC contours represent different percentage of perennial ice: light green for 60%, green for 70%, orange for 80%, and brown for 100%. Buoy drift tracks include IMB buoys 2006B, 2006D, and 2006E, and Argos buoy ID 5317. Each buoy track is marked with green + for the monthly averaged location (MAL) in September 2006, green circle for the MAL in March 2007, and black dots for MAL of the months in between. The red triangle denotes the last known location of 2006B when it was lost in 30 January 2007.

extent decreased more rapidly as suggested by the long-term DM estimates (Figure 3). This DM rapid decreasing rate is consistent with the perennial ice loss observed in the past 8 years with QSCAT data.

4. Discussion

[14] Sea ice dynamics observed in the animation of QSCAT daily maps of sea ice from November 2006 to March 2007 (Animation 1) indicates that perennial ice curved around the Beaufort Sea and the Bering Sea toward the Transpolar Drift (TD), loading ice into the TD. This ice dynamic pattern was verified, for example, by the drift track of Argos buoy 5317 in the Beaufort Sea (Figure 2). The TD transports sea ice from the East Arctic to the West Arctic Ocean over the Fram Basin across the North Pole, resulting in ice export out of Fram Strait [*Weatherly and Walsh*, 1996]. The map of the TD, approximately along the drift tracks of IMB buoys 2006D and 2006E (Figure 2), and other surface currents in the Arctic Ocean have been published elsewhere [*Loeng et al.*, 2005; *Rigor et al.*, 2002]. On the other side of the TD, Animation 1 also revealed the push of perennial ice from north of Franz Josef Land and Spitsbergen toward the TD. The loading of perennial ice into the TD from both sides enhanced the capacity of the TD to transport ice through Fram Strait in the east of Greenland to lower latitudes where the ice was melted by warm Atlantic waters.

[15] The elongated and narrow feature of mixed and perennial ice, stretching along the east side of the North Land (Severnaya Zemlya) between the Kara Sea and the Laptev

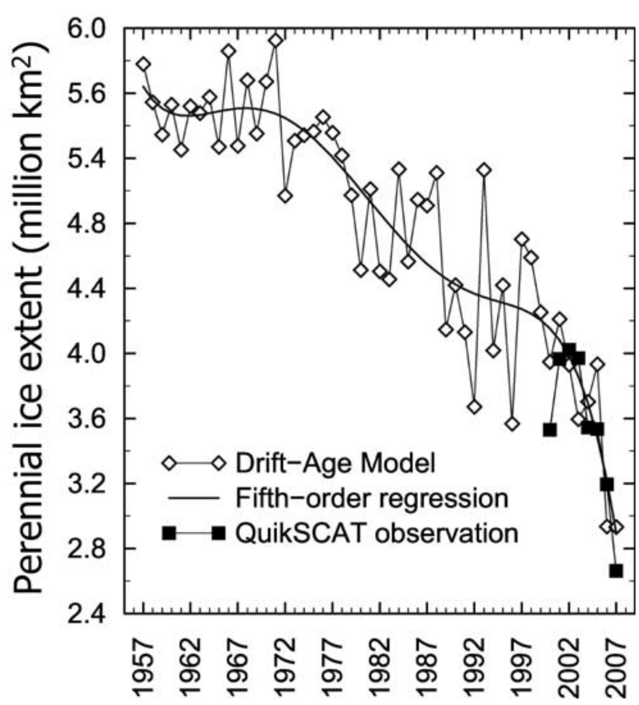

Figure 3. Time-series of area of perennial sea ice extent in March of each year estimated by the Drift-Age Model (with a fifth-order regression) and observed by QuikSCAT satellite scatterometer within the model domain. In each year, the model result was an average over March, and the satellite observation was on the spring equinox (21 March).

Sea in the East Arctic, detached from the coast, and drifted toward the TD while shifting pole-ward toward the West Arctic as observed in Animation 1. Consistent with the pole-ward shift of the ice pack toward the West Arctic, ice drift tracks of IMB buoys 2006D and 2006E (Figure 2) revealed such ice migration, confirming QSCAT observations.

[16] Results from IMB buoy 2006B showed its drift from its deployed location near the North Pole in late April 2006 and then rapidly moving from its September location out of Fram Strait to the final position at 78.173°N and 1.351°W when it was lost on 30 January 2007 (Figure 2). In January 2007, the buoy drifted from a location at 82.880°N and 6.052°E to its final place, crossing a flux gate spanning 400 km across Fram Strait at about 81°N [*Kwok and Rothrock*, 1999]. This buoy drift covered a distance of 531 km with an average drift speed of about 17.7 km per day. Given the broad correlation length scale for sea ice motion, the estimated ice extent loss was 0.21×10^6 km^2, consisting mostly of perennial ice as observed from Animation 1. This buoy estimate compares well with the perennial ice loss of 0.19×10^6 km^2 calculated from QSCAT data for January 2007. The ice loss in January 2007 was also consistent with a northerly wind anomaly of as much as 5 m $\cdot$ s^{-1}, double the January wind averaged over 50 years from the National Centers for Environmental Prediction (NCEP) reanalysis. The loading and enhancement of the TD had occurred with a much more pronounced short-term effect in September 2005 causing an abrupt ice loss via Fram Strait [*Nghiem et al.*, 2006a, 2006b]. The TD transport of ice in 2005 was accelerated by a strong northerly wind anomaly in September 2005 observed in data from the NCEP reanalysis over the past 50 years along the Greenland Sea [*Nghiem et al.*, 2006b]. On the two different sides of the TD, a pronounced atmospheric low pressure over the Barents Sea, in concert with a strong high pressure over the Canadian Basin, set up the wind anomaly [*Nghiem et al.*, 2006b]. These atmospheric anomalies loaded ice into the TD and accelerated the TD like a runaway train carrying ice out of the Arctic, noted here as the 'Polar Express' (PE).

[17] In addition to rapid ice loss by the PE, ice export to Baffin Bay was also observed by QSCAT (Animation 1). Furthermore, the convergence of sea ice by ice loading toward the TD and the compression from the East to the West Arctic contributed to the reduction in the extent of perennial ice.

[18] The shift in the Arctic Ocean from perennial to thinner seasonal ice suggests a coincident decrease in surface albedo and more solar energy absorbed in the ice ocean system during summer melt [*Perovich et al.*, 2002, 2007]. As such, the change in winter preconditioned the sea ice cover for more efficient melt and further ice reduction in summer. Winter preconditioning of summer sea ice coverage was associated with the North Atlantic Oscillation (NAO) [*Partington et al.*, 2003] and with the Arctic Oscillation (AO) [*Rigor et al.*, 2002]. The NAO index in positive phases is also correlated to the areal flux of ice export through Fram Strait [*Kwok and Rothrock*, 1999]. The monthly AO index also exhibited mostly positive values during September to November 2005 and March 2006 to March 2007, a pattern which enhances ice advection away from the coast of the East Siberian and Laptev Seas and increases ice export out of Fram Strait [*Rigor et al.*, 2002]. A warming trend, increasing long-wave radiation, and Atlantic water intrusion in various regions over the Arctic Ocean have been reported [*Richter-Menge et al.*, 2006]. These thermodynamically induced changes to the ice cover may in turn be impacting ice dynamics, with the thinner ice exhibiting enhanced motion and export by the PE. Dynamic and thermodynamic effects appear to be combining to expedite the loss of Arctic sea ice as evident in QSCAT observations of a faster reduction rate and a 10% decrease in total ice extent by the first week of August in 2007 compared to those at the same time in 2005 and 2006.

[19] The dramatic changes in Arctic ice composition and the record reduction of perennial ice require an urgent reassessment of recent sea ice forecast model predictions and of the impacts to local weather and climate, as well as to shipping and other maritime operations in the region. Observations of perennial ice loss were based on past data from satellite sensors and Arctic buoys. Simply extrapolating past observations is not sufficient to forecast sea ice change, and physical insights and understanding of complex Arctic processes and interactions are necessary to improve ice forecast models. In this regard, coordinated research efforts under the International Polar Year Program are most timely.

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