RETREAT OF ARCTIC SEA ICE FROM SATELLITES, IN SITU OBSERVATIONS, AND A DRIFT-AGE MODEL

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The retreat of Arctic sea ice was predicted to be one of the first indicators of climate change. Observations from satellites show that Arctic sea ice has declined to record minima in total extent and fraction of perennial sea ice area during the last decade (e.g. NSIDC, 2009; Nghiem et al. 2009; and Nghiem et al. 2007). However, while sea ice extent can readily be obtained from satellites, we are only now developing our capability to remotely monitor sea ice thickness. Sea ice thickness estimates obtained from satellites (freeboard) provide basin-wide estimates of thickness, however, these estimates require careful validation. *In situ* observations of sea ice thickness, e.g. by submarines and drifting buoys, are more accurate; however, these observations are sparse in space and time. Comparisons of the retrievals of sea ice thickness estimates from ERS and ICESat satellites with *in situ* observations collected by submarine cruises under the sea ice, by direct measurement during field camps by electromagnetic induction sounding instruments flown over the sea ice, and by buoys drifting with the sea ice show good agreement between these estimates of the thickness of sea ice (e.g. Rigor 2005; Haas et al. 2008; Kwok et al. 2009).

In order to bridge the gaps in space and time between *in situ* and remote estimates of sea ice thickness, we have been developing a Drift-age Model (DM). The DM moves parcels of sea ice around the Arctic Ocean using gridded fields of ice motion, and if these parcels stay within the summer minimum ice extent, these parcels are aged one year (Rigor and Wallace, 2004). This DM has been used to understand the recent changes in sea ice extent. Typically, variations in sea ice extent have been attributed to the Arctic Oscillation (AO, Thompson and Wallace, 1998; Rigor et al. 2002; Drobot and Maslanik, 2003). However, despite more moderate AO conditions, record or near-record minima in sea ice extent continue to occur. In order to explain this, Rigor and Wallace (2004) used the DM to show that the area covered by older, thicker sea ice across the Arctic Ocean decreased from covering over 80% of the Arctic Ocean prior to 1989, to about 40% of the Arctic Ocean in the early 1990's. This younger sea ice was shown to drift towards the Alaskan coast where the ice did not have enough mass to survive the summer melt. In a series of papers, we have assessed the accuracy of the DM. For example, Rigor (2005) showed that the thickness of sea ice retrieved from ERS satellites (Laxon et al. 2003) increased rapidly for younger sea ice classes as expected, and continued to increase in thickness to over 4 meters over 20 years. The increase in the thickness of sea ice with age was attributed to dynamic events, which increased the areal coverage of ridged and rafted sea ice. This is corroborated by Rigor (2005) and Haas et al. (2008) who show that the *in situ* thickness distributions of sea ice shifts to include more ridged and rafted ice types in areas of older sea ice. Nghiem et al. 2007 showed basin-wide agreement between the areal distribution of the age of sea ice and areal distribution of the sea ice types (first-year, and multi-year) retrieved from QuikSCAT; however, they also noted regional differences during times and in areas of sparse buoy coverage. To address this issue, the gridded fields of ice motion used to force the DM are now assimilating ice drift retrieved from passive microwave satellites following the procedures of Maslanik et al. (1998) and Kwok (2008). We are also using a new sea ice concentration analysis (Webster et al. pers. comm.) and ice charts from the National Ice Center to determine which areas of sea ice survive and age another year.

The improved DM shows that the last remnants of sea ice that were at least 10 years old disappeared from the Arctic Ocean by the end of the summer of 2008. The basin-wide average age of sea ice decreased from ~15 years old prior to 1989, to ~10 years old by the mid-1990s. Given the recent record or near-record summer minima and the predominance of first-year ice across the Arctic Ocean, the average age of sea ice is now less than 2 years old. We estimated the thickness of sea ice across the Arctic Ocean based on the estimated age of sea ice provided by the DM and the relationship between the age and thickness of sea ice (e.g. Rigor 2005). The decline of sea ice thickness is tempered by the rapid growth of younger, thinner sea ice. The basin-wide average thickness of sea ice during March decreased from over 3.5 meters prior to 1989, to 3 meters in the mid-1990s, and is now estimated to be less than 2.5 meters.

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