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Mass Balance of Multiyear Sea Ice in the Southern Beaufort Sea

PI Andrew R. Mahoney
Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, Alaska 99775-7320
phone: (907) 474-5382 fax: (907) 474-7290 email: Mahoney@gi.alaska.edu

Award Number: N000141210470
http://seaice.alaska.edu/gi/

LONG-TERM GOALS

1) Determination of the net growth and melt of multiyear (MY) sea ice during its transit through the southern Beaufort Sea
2) Identification of key regional processes in southern Beaufort Sea affecting MY ice recruitment
3) Improved predictability of the future states of the Arctic ice pack

OBJECTIVES

We have four main scientific objectives:

I) <u>Estimation of MY ice volume entrained into the Beaufort Sea from north of Canada</u>

The region north of the Canadian Archipelago contains some of the oldest and thickest ice in the Arctic and the amount of this ice imported into the Beaufort Sea has a significant effect on the overall MY ice budget of the Arctic.

II) <u>Estimation of rate of thinning of MY ice during transit through southern Beaufort Sea</u>

The thickness of MY ice at the end of its westward transit through the Beaufort Sea will have a critical impact on the volume of MY ice recruited from one year to the next and on navigability in the Beaufort and other marginal seas.

III) <u>Assessment of contribution of refreezing of meltwater to overall mass balance of MY ice</u>

Meltwater created through surface ablation can refreeze if it finds its way underneath the sea ice where the ocean will typically be at the colder freezing point of seawater. This can create ice lenses and false bottoms beneath the sea ice and make a positive, but poorly-understood, contribution to the mass balance

IV) <u>Assessment of the role MY ice dispersal in promoting ice loss</u>

We speculate that diminished MY ice in the Beaufort Sea may be a consequence of changes in drift patterns. Moreover, if net drift and divergence increase as MY ice extent decreases, this *may represent a feedback process that will accelerate the Arctic's trajectory toward a seasonally ice free state.*

APPROACH

Overview

To address our four main scientific objectives, we are employing a data fusion approach using a range of public-domain in-situ and remote sensing datasets.

Fusion of ice draft and drift data

Combining ice drift and ice thickness data is a central step toward addressing our first two research objectives. In order to calculate the flux of MY ice entering the Beaufort Sea (Objective I), we must know both the thickness and velocity of this ice. Similarly, to determine the rate of thinning of MY ice that takes place in the southern Beaufort Sea (Objective II), we need to know the thickness of MY ice floes at different times and locations. So far, our efforts have focused on this latter problem, which we are addressing by using data from the International Arctic Buoy Program (IABP) to find occasions when an ice floe makes contact with of one of four moored ice profiling sonars (IPSs) that make up part of the Beaufort Gyre Exploration Project (BGEP). We define a contact event as the closest point of approach during a period when a buoy passes with 30 km of a mooring. We then identify cases where buoys make multiple such contacts, allowing us to derive repeated measurements of the ice thickness of a particular field of sea ice.

To derive ice thickness distributions for each contact event, we must transform the timeseries of ice draft recorded by the moored IPS into a spatial series by multiplying by the velocity of the ice drifting above the mooring. Melling *et al.* (1995) describe a method for doing this using an Acoustic Doppler Current Profiler to track the motion of underside of the sea ice. However, ADCPs were not deployed on all BGEP moorings and ice velocity data from the ADCP-equiped moorings are not currently available. Instead, we use satellite-derived gridded daily ice velocities (*Fowler*, 2003). These data use cross correlation of passive microwave and visible satellite imagery to derive 2-dimensional motion vectors. An optimal interpolation scheme is used to combine these results with IABP buoy velocities. The daily velocities are calculated on a 25 km grid, with individual error variances obtained from the interpolation process. For the purpose of generating spatial series of ice draft at each mooring, we linearly interpolated these ice velocity data both spatially and temporally.

Analysis of ice core and airborne electromagnetic (AEM) data

Starting in 2007, the Seasonal Ice Zone Observing Network (SIZONet) has conducted airborne electromagnetic-induction thickness surveys in conjunction with surface-based measurements out of Barrow, Alaska to track changes in the composition of the ice pack. By conducting visual ice observations during the AEM surveys, sections of the data containing MY ice can be extracted and analyzed separately. Between AEM missions, additional flights were made to allow surface measurements of ice thickness and the collection of ice cores from representative MY ice floes. Through stratigraphic analysis of these cores, we identify annual layers that help constrain the age of the ice, which in combination with drift data allows us to estimate the origins of MY ice in the Beaufort Sea. Ice core samples that are brought back to shore were melted and used to determine profiles of salinity and stable isotope ratios. These data allow us to identify layers of refrozen melt water that once pooled beneath the ice. These meltwater layers, traces of which are found in all multiyear ice cores, form part of the annual accretionary layers and contribute to the total mass budget of level ice in the region. Identifying such layers will help interpretation of data from IMBs, which may overestimate ice thickness in the presence of false bottom or under-ice melt ponds. This analysis will be fundamental to achieving objective III.

Analysis of thickness changes in context of ice deformation

In order to better understand the processes affecting the concentration of MY ice in the Beaufort Sea, we will examine changes in thickness distribution in the context of data from high-resolution drift data from the SEDNA project and an NSF AON project (Hutchings and Rigor, ARC 1023662, 01/01/2011-12/31/2014). Combining drift data from closely-spaced buoys with synthetic aperture radar (SAR) data, SEDNA has been able to capture meso-scale deformation of sea ice in the Beaufort Sea (Hutchings et al., 2011).

In other work led by Co-I Hutchings, Divergence of the ice pack has been estimated at the scale of the buoy spacing throughout the Beaufort Sea by tracking buoy triads. Green's Theorem is then used to calculate strain-rate following Hutchings et al (2012). Sub-daily divergence monitoring is required as lower resolution products (such as those derived from satellite data) under-estimate ice growth in leads (Hutchings et al., 2011). Divergence of sea ice allows new ice growth in leads, which affects the rheological properties of the ice pack and in turn affects sea ice dynamics potentially leading to increased divergence. We have found that the rate of shear increased in the Beaufort Sea, and the variance of divergence has increased. These results are being prepared for submission to JGR-Oceans (Hutchings and Martin, in prep). The implications of these finding is that new ice production has been enhanced since 2006. The resulting increased fraction of thin FY ice would enhance summer melt rates, setting up a regional feedback process consistent with that suggested by Shimada *et al*. (2006). The comprehensive dataset of in situ observations from the Beaufort Sea offers a unique opportunity to identify and quantify regional feedbacks between ice dynamics and mass balance, which will be critical in the predictability of ice conditions of timescales of 5-10 years.

WORK COMPLETED

Compilation of datasets has comprised a significant proportion of the effort made on this project to date. In particular, analysis of IABP data has required assembling a database of buoy metadata from individual monthly reports. This database has proven necessary to uniquely identify buoys in order to establish the type and origin of each and produce individual drift tracks. Table 1lists the data acquired so far.

Table 1: Datasets compiled to date

Geophysical data type	*Source*	*Time period acquired*
Buoy tracks	IABP	12 hrly position data 1978-2012
Ice thickness	SIZONet	April campaigns 2007-13
Ice thickness	BREA	April campaigns 2012-13
Ice draft	BGEP	2003-2012
Aerial photography	NASA IceBridge	Arctic sea ice flights 2011-12
Sea ice concentration	NSIDC	1978-present
Gridded ice drift	NSIDC	1978-present
Ice core data	SIZONet	April campaigns 2007-13
Ice mass balance buoys	IABP/CRREL	1993-2012

In addition to acquiring the data files, we have also developed data fusion algorithms, for example, to convert timeseries of BGEP ice draft data into spatial series using gridded velocity data; and then to identify subsets of these data corresponding to contact events when a buoy drifts within 30 km.

RESULTS

Due to page limitations, we present results below only pertaining to the data fusion analysis of buoy, mooring and satellite data desribed above.

Thinning of Beaufort Sea MY ice during the summer of 2007

Figure 1 shows the tracks of two IABP buoys, both deployed in the Beaufort Sea in August 2006, together with the locations of four moored IPSs. Buoy 64879 was deployed as part a cluster of Sea ice

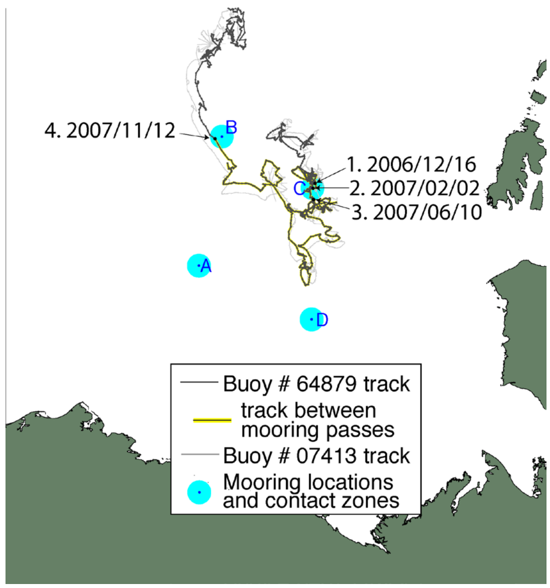

Figure 1: Drift tracks of buoys 64879 and 07413 and locations of moored IPSs. Labeled dots indicate the closest point of approach during contact events on the date indicated

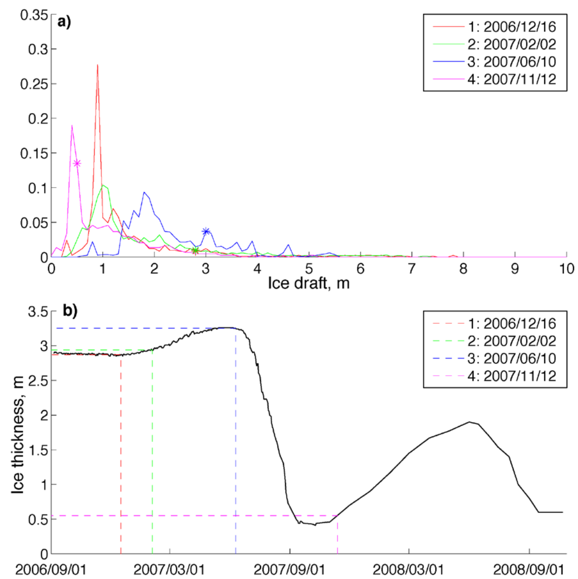

Figure 2. a) ice draft distributions derived from IPS data centered on each contact event. Asterisks indicate the draft bin equivalent to the thickness measured by the nearby IMB. b Ice thickness measured by buoy 07413. The colored dashed lines indicate the ice thickness at the contact times for buoy 64879.

Experiment - Dynamic Nature of the Arctic (SEDNA) buoys designed to analyze high resolution motion and dispersion of sea ice. And subsequently made multiple contacts with moored IPSs. After deployment, it drifted south and made contact with mooring C on December 16, 2006 at a distance of 13.7 km. It remained in the same vicinity for the next several months making two more contacts with mooring C on February 2 and June 10, 2007. Buoy 64879 then continued drifting south before reversing course in August 2007 and heading toward mooring B, where it made contact on November 12, 2007. These four contact events are labeled 1-4 in Figure 1. Buoy 07413 was an ice mass balance buoy (IMB) that was deployed in a MY ice floe at the center of the SEDNA cluster. At deployment, buoys 64789 and 07413 were separated by approximately 20km and this had increased to 41 km at the time of contact event 4. Therefore, although buoy 07413 did not make contact with any moorings, we can use its ice thickness measurements to interpret changes in the thickness distribution of ice around buoy 64879.

Figure 2 shows the ice draft distributions for 30 km sections of IPS data centered on the time of each contact event. The asterisks on each distribution denote the draft corresponding to the thickness of ice measured at the same time by IMB 07413, calculated assuming ice and snow densities of 900 and 300 kg m^{-3}, respectively. These asterisks help identify modes that correspond to MY ice. The timeseries of ice thickness recorded by IMB 07413 is shown in Figure 2b, with dashed lines indicating the timing of each contact event. The ice thickness distributions corresponding to contact events 1-3 (red, green and blue lines, respectively) show primary modes at 0.9 m, 1.0 m and 1.8m, which we interpret as representing the growth of first year (FY) ice over the 2006-07 winter. The ice thickness distribution at contact event 4 (magenta line) shows a primary mode 0.4 m, which is close to the ice draft measured at the nearby IMB indicating that this mode represents thin MY ice event that barely survived the 2007 summer.

By examining the tails of the distributions corresponding to contact events 3 and 4 more closely, we can estimate the amount of thinning experienced by the thickest ice around buoy 64879 during the summer of 2007. Figure 3a shows the drafts distributions for contact events 3 and 4 rescaled such that the frequency corresponding the MY ice modes is equal to 1 for both distributions. The complete distributions are shown by the thin solid lines, while bold lines indicate the tails of these distributions. The dashed lines indicate exponential functions fitted to the tails of the distribution. To estimate the thinning experienced by ice thicker than the MY mode, we calculated the decrease in draft necessary to transpose the fitted curve for contact event 3 (2007/06/10) onto the curve for contact event 4 (2007/11/12). The result, which will always be linear when subtracting two logarithmic functions, is shown in Figure 3b. This indicates that the loss of ice would have equaled the initial ice thickness for ice with a draft of 2.42 m.

So far, we have found 12 IABP buoys that made multiple contacts with BGEP moorings, though only one that had an IMB nearby to validate the thickness changes observed. However, the example above is promising we are hopeful that this approach will allow us to further study the thickness changes of MY ice the Beaufort Sea on other occasions.

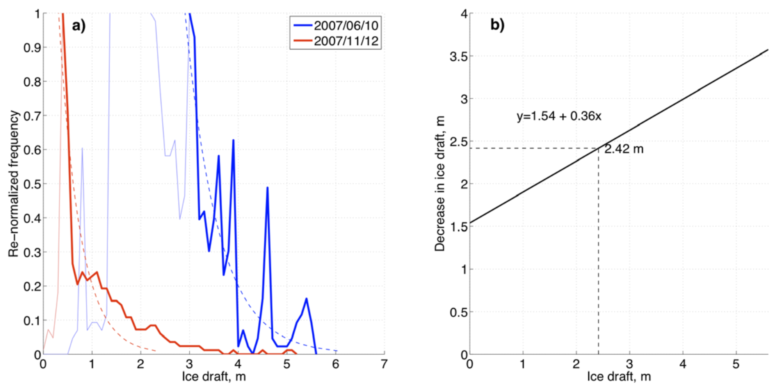

Figure 3a) Re-normalized ice draft distributions from contact events 3 and 4, scaled such that the frequency corresponding to the MY ice modes is equal to 1 for both distributions. The tails of the distributions showing ice thicker than the MY ice mode are shown by the bold lines. Dashed lines represent exponential fits to the re-scaled tails. b) Decrease in ice draft between contact events as a function of original draft.

IMPACT/APPLICATIONS

We anticipate our future results will improve understanding of the fate of multiyear sea ice in an increasingly seasonal ice pack and lead to reduced uncertainty in sea ice forecasting. We are currently preparing manuscripts presenting the results of our analysis of repeat buoy contacts with moored IPSs and the analysis of MY ice core age, thickness and stratigraphy.

RELATED PROJECTS

PI Mahoney is involved in the NASA-funded The Marginal Ice Zone Observations and Processes EXperiment (MIZOPEX; http://ccar.colorado.edu/mizopex/). This project will use multiple unmanned aircraft to obtain a variety of data over the marginal zone in the Beaufort Sea. Mahoney's involvement focusses on the analysis of sea ice data.

PI Mahoney and co-I Eicken are leading the Seasonal Ice Zone Observing Network (SIZONet) project. Data from this project will provide additional calibration and validation data to interpret airborne electromagnetic induction and ice-profiling sonar from the region. The project also contributes ice thickness and ice core data sets analyzed in this study.

Co-I Hutchings is leading the NSF-funded project Sea Ice Deformation Observation with an AON, which is assessing the capabilities of the current Arctic buoy network to resolve sea ice deformation and designing a network of GPS-enabled buoys to short-timescale motion and deformation events.

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