MIZMAS: Modeling the Evolution of Ice Thickness and Floe Size Distributions in the Marginal Ice Zone of the Chukchi and Beaufort Seas

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LONG-TERM GOALS

Our long-term goal is to develop a robust, high-resolution coupled sea ice–ocean modeling and assimilation system that is capable of accurately predicting sea ice conditions in the marginal ice zone (MIZ) of the Chukchi and Beaufort seas (CBS) on seasonal time scales. Our primary interest is the ability to realistically simulate the evolution of the multicategory ice thickness and floe size distributions (ITD, FSD) jointly in the CBS MIZ. Particularly, we would like to improve model physics to represent changes in FSD due to ice advection, thermodynamic growth or decay, lateral melting, ridging and rafting, and wave-induced fragmentation through theoretical development and numerical implementation.

OBJECTIVES

Our main scientific objectives are to:

(1) Examine the historical evolution of the CBS MIZ ice–ocean system and its ITD and FSD from 1978 to the present to quantify and understand the large-scale changes that have occurred in the system.

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(2) Identify key linkages and interactions among the atmosphere, sea ice, and ocean, to enhance our understanding of mechanisms affecting the CBS MIZ dynamic and thermodynamic processes.

(3) Explore the predictability of the seasonal evolution of the MIZ and the summer location of the ice edge in the CBS through seasonal ensemble forecast.

(4) Explore the impacts of future anthropogenic global climate change (including a summer arctic ice-free regime) on the CBS MIZ processes through downscaling future projection simulations.

APPROACH

To address the scientific objectives, we plan to develop, implement, and validate a new coupled ice–ocean **M**arginal **I**ce **Z**one **M**odeling and **A**ssimilation **S**ystem (**MIZMAS**) that will enhance the representation of the unique MIZ processes by incorporating a FSD and corresponding model improvements. A successful incorporation of a FSD will allow MIZMAS to simulate the evolution of both ITD and FSD at the same time. The development of MIZMAS will be based on systematic model parameterization, calibration, and validation, and data assimilation, taking advantage of the integrated observational and modeling efforts planned by the ONR MIZ research initiative. Meanwhile, we also uses the **P**an-arctic **I**ce/**O**cean **M**odeling and **A**ssimilation **S**ystem (**PIOMAS**), a variant of MIZMAS, to study changes in the Arctic sea ice and ocean system. With a coarser model resolution than MIZMAS, PIOMAS is more computationally efficient in process studies. Jinlun Zhang, Axel Schweiger, Mike Steele at the University of Washington are investigators of this project. Harry Stern at UW also helped in analyzing satellite images of sea ice floes and deriving FSD. In addition, an undergraduate student at UW, Margaret Stark, has been hired to process satellite images of sea ice.

WORK COMPLETED

We developed an ensemble seasonal forecast system for predicting Arctic sea ice weeks to months in advance using MIZMAS that has high-resolution coverage for the CBS. To obtain "best possible" estimates of sea ice and ocean states as initial conditions for seasonal forecast, this forecast system assimilates satellite sea ice concentration and sea surface temperature and performs near real-time hindcast. The atmospheric forcing for the ensemble forecasts consists of NCEP/NCAR reanalysis data from the past seven years, which represents recent climate conditions and is used to drive MIZMAS to create an ensemble of seven predictions. The median of the seven ensemble predictions is taken as the forecast outcome (Zhang et al., 2008). We tested this system by conducting a number of forecasts for sea ice conditions in July–September 2013. We are to analyze the performance of these forecasts and make adjustment if necessary to improve the system so that it may be useful to assist the planned 2014 MIZ field campaign.

We have assembled and evaluated a multi-sensor remote sensing data set for the melt season of 2013. We have assessed the suitability of high resolution (3.125 km footprint) passive microwave data, MODIS visible band images (250 m), RadsarSat II ScanSar (50 m), and high resolution TerraSar X (2.75 m) and optical images (1 m) assembled through the MEDEA project, to provide data to develop and validate MIZMAS. Radsarsat 2 ScanSar and high resolution TerraSar-X images were collected as part of the MIZ 2013 pilot project at weekly intervals. AMSR-2 passive microwave derived ice concentrations data from an innovative new product developed by the University of Hamburg which generates ice concentration data at 3.125 km resolution were extracted. Cloud free images from high resolution optical sensors (1 m resolution) were made available through the MEDEA project. All images were remapped to common projection and mosaics constructed to allow for intercomparison of sea ice features.

We assembled a data set of MODIS 250 m resolution images, identified cloud free areas, and extracted regions that showed identifiable ice floe structures. The data set currently spans 150 images from February through September of 2013 with 240 extracted identified cloud free regions.

We developed a methodology to extract sea ice floe parameters (shape, size). The method is based on thresholding and morphological operations for identification of objects. Objects are then characterized by area, perimeter, mean caliper diameter (MCD) and statistical shape descriptors. The method has been applied to a subset of MODIS images.

We examined dates of melt-back in the Beaufort Sea using passive microwave images and investigated forcing mechanisms of this melt-back.

We continued to work on the incorporation of FSD into MIZMAS. We are trying to determine the optimal upper and lower limits of the size categories in FSD. Characteristics of ice floes in satellite images of varying resolutions are used for the determination. We have set up PIOMAS for test runs of FSD, which is more computationally efficient for repeated model sensitivity integrations.

We studied the impact of the intense August 2012 cyclone on Arctic sea ice retreat. We tried to quantify the effects of cyclone enhanced ocean mixing and bottom melt on the new record low Arctic sea ice extent in summer 2012. The paper was published in Geophysical Research Letters (Zhang et al., 2013).

We completed a collaboration with Dr. S. Laxon at University College London and others to compare PIOMAS derived Arctic sea ice thickness and volume with satellite CryoSat-2 estimates. Results from this collaboration were published in Geophysical Research Letters (Laxon et al., 2013).

We collaborated with Dr. C. Peralta-Ferriz at University of Washington and others to study the spatiotemporal variability of Arctic Ocean bottom pressure anomalies over the period 2002–2011. PIOMAS results are compared with satellite mission GRACE derived bottom pressure data. Results from this collaboration have been submitted to J. Climate (Peralta-Ferriz et al., 2013).

We collaborated with Dr. G. Schmidt and the Goddard Institute for Space Studies (GISS) climate model development team for improving the GISS ModelE2. Zhang developed an efficient sea ice model based on a generalized curvilinear coordinate system that was specifically designed for the GISS ModelE's Arakawa C-grid. The sea ice model was provided to the GISS team and incorporated into ModelE. The GISS ModelE2 model has contributed to the Coupled Model Intercomparison Project (CMIP5) archive for the IPCC Fifth Assessment Report (AR5). The work to contribute to AR5 has resulted in three manuscripts that are submitted to Journal of Advances in Modeling Earth Systems (Miller et al., 2013; Nazarenko et al., 2013; Schmidt et al., 2013).

RESULTS

Modeling:

We are interested in working towards accurate forecast of the location of ice edge in the CBS using the MIZMAS based seasonal ensemble forecast system. In a test ensemble forecast starting on June 1, 2013, we found mixed results in MIZMAS' performance in predicting ice edge location three months later on September 2, 2013 (Figure 1). MIZMAS appears to be able to reasonably predict ice edge location in part of the Chukchi, East Siberian, and Laptev seas, when compared to satellite passive microwave observations of ice edge. However, it may over-predict ice coverage in the Beaufort Sea, even though passive microwave data tend to under-estimate ice coverage in the MIZ. This highlights the challenge in predicting the location of the ice edge with a relatively long (3 months) prediction range. The over-prediction of ice extent in the Beaufort Sea may suggest the necessity of introducing FSD into the model to better simulate lateral ice melt in the region.

We conducted a model study to quantify the impact of an intense early August cyclone on the 2012 record low Arctic sea ice extent. The cyclone passed over the Arctic at a time when the simulated Arctic sea ice was thin and the simulated Arctic ice volume had already declined ~40% from the 2007–2011 mean. The thin sea ice pack and the high heat content of the near surface temperature maximum layer created conditions that made the ice particularly vulnerable to storms. During the cyclone, ice volume decreased about twice as fast as usual, owing largely to a quadrupling in bottom melt caused by increased upward ocean heat transport. This increased ocean heat flux was due to enhanced mixing in the oceanic boundary layer, driven by strong winds and rapid ice movement. A comparison with a sensitivity simulation driven by reduced wind speeds during the cyclone indicates that cyclone-enhanced bottom melt strongly reduces ice extent for about two weeks, with a declining effect afterwards (Figure 2). The simulated Arctic sea ice extent minimum in 2012 is reduced by the cyclone, but only by 0.15×10^6 km^2 (4.4%). Thus without the storm, 2012 would still have produced a record minimum. These results have been published (Zhang et al., 2013).

Remote Sensing:

We found that AMSR-2 ice concentration data from the Hamburg 3.125 km product provide a useful tool for studying evolving MIZ. Comparisons with SAR and MODIS data showed that the ice edge is represented in very good detail in this product and the evolution of the MIZ during a storm that occurred between July 22 and 26, 2013 seems to be well captured (Figure 3). However, time series of the data reveal several rapid transitions that appear to be spurious and are likely related to weather or melt-pond variability. In addition, ice concentrations within the ice pack can show values as low as 60% when MODIS and SAR data indicate a near 100% ice concentrations. A careful filtering and cross-checking with other data will therefore be necessary for validation purposes.

We have demonstrated the extraction of ice characteristics from cloud free regions in MODIS 250 m images (Figure 4). We find that 90% of the ice floes have convexity parameter of > 0.85, which is relatively high, and smaller floes tend to be more convex than larger floes. For floes with MCD larger than about 1 km, the size distribution is either exponential or power-law.

Intercomparison of SAR, MODIS and high resolution optical images from the MEDEA projects have demonstrated the scale dependency of detecting "floes". Collocated MEDEA images have revealed detailed floe structure that is not detectable in any of the other image types. However, MEDEA images only provide information at spatial scales of the order of 15 km or so. In order to provide suitable information for the validation of sea ice characteristics in MIZMAS, we will need to design strategies that connect the model scale with the scale and coverage provided by observations. We plan to further examine MEDEA, SAR and MODIS images to establish the scale relationship. Figure 5 provides an example of MIZ features at different resolutions.

Wind forcing of ice edge variability:
The earliest melt-back in the Beaufort Sea occurs in its southeast quadrant, ie to the northeast of the Mackenzie River delta, west of Amundsen Gulf, and southwest of Banks Island (Figure 6). Why is this? Previous work (Lindsay and Zhang, 2005) indicated that wintertime off-shore winds create a "thin ice polynya" in this region which is thus "pre-conditioned" to early melt-back in spring/summer. We have investigated this idea in further detail. We find that in April, just before the melt season, sea ice is indeed thin in this area (Figure 6). As suspected, the cause is off-ice, westward winds during the growth season. The strongest such winds occur in fall (Oct-Dec) and again in spring/early summer (Apr-Jun), with a long quiescent period in Jan-Mar (Figure 6). These winds create a region of thin ice in the southeast Beaufort Sea which is then more likely to melt out earlier than other areas in response to both thermodynamic forcing (solar radiation and warm Mackenzie River water discharge) and dynamic forcing (westward, off-shore winds). That is the story for the mean. In addition, we have found that interannual variability is largely forced by these growth-season winds, which makes sense given the relatively small interannual variability in monthly mean river discharge and solar radiation. Figure 6 shows that April zonal winds predict the month of melt-back in this area with 95% confidence. That is, the stronger the April-mean westward winds, the more likely it is to have an early ice retreat at this location (and same for northward winds, although with lower significance). We are still investigating the role of fall winds in this melt-back variability, and the role of initial ice thickness in April.

IMPACT/APPLICATIONS

The objectives of this project address directly some of the key questions raised in the ONR MIZ research initiative: ***Emerging Dynamics of the Marginal Ice Zone***. These questions are explored by modeling, analyzing, and understanding the large-scale changes that have occurred in the CBS MIZ, and by assessing the possible changes that lie ahead. Aiming to improve our understanding of the CBS MIZ processes, interactions, and feedbacks, this ONR MIZ research contributes to the inter-agency Study of Environmental Arctic Change (SEARCH). Aiming to enhance model physics, this research addresses the U.S. Navy's needs to improve the predictability of sea ice in the region. A successful development of MIZMAS will mark a new sea ice model that is able to explicitly simulate the evolution of multicategory ice thickness and floe size distributions simultaneously. The theoretical and numerical work on FSD will provide a foundation to improve significantly the representation of key MIZ processes. This will be a significant step forward towards developing the next generation of sea ice models for use in operational forecast and climate predictions.

RELATED PROJECTS

Supported by NASA and in collaboration with Drs. Carin Ashjian, Robert Campbell, Victoria Hill, Yvette Spitz, Zhang and Steele are investigating planktonic ecosystem response to changing sea ice and upper ocean physics in the CBS. We are modeling the integrated system of sea ice, ocean, and marine ecosystem in the CBS (http://psc.apl.washington.edu/zhang/Chukchi_Beaufort/model.html).

Supported by NSF, Zhang and R. Lindsay are conducting numerical experiments for seasonal ensemble forecasts of Arctic sea ice. The main goal of this project is to improve the seasonal predictability of Arctic sea ice (http://psc.apl.washington.edu/zhang/IDAO/seasonal_outlook.html).

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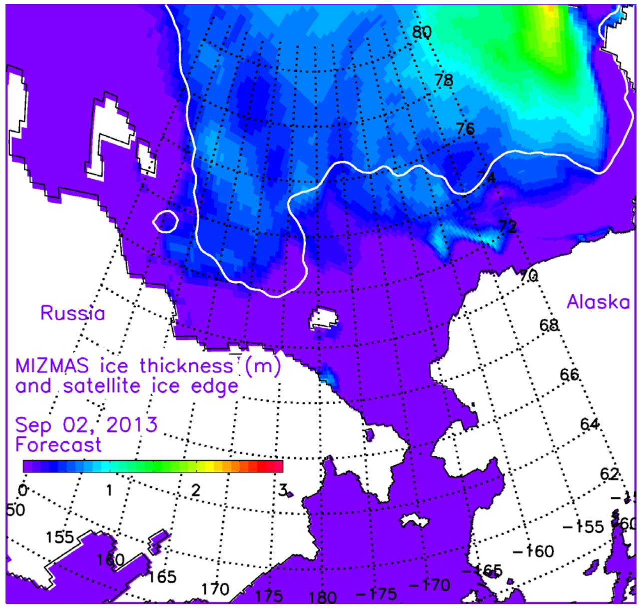

Figure 1. MIZMAS ensemble median prediction of sea ice thickness (colors) and satellite passive microwave observations of ice edge (white line) in the Pacific sector of the Arctic Ocean on September 2, 2013. Ice edge is defined as the contour of 0.15 ice concentration derived from passive microwave data. The prediction starts on June 1, 2013, and so the prediction range is three months.

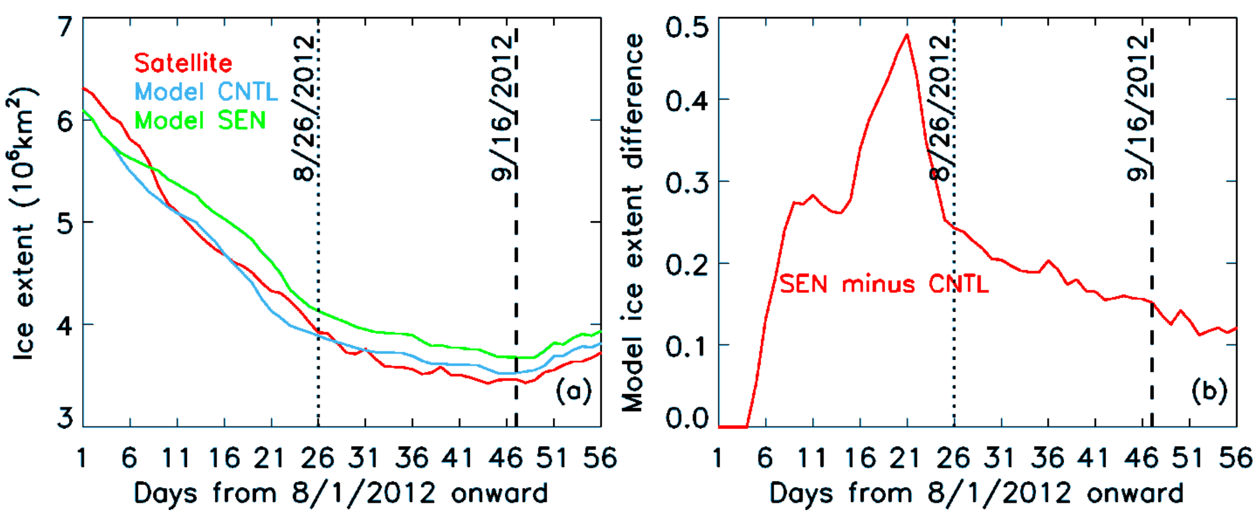

Figure 2. Satellite observed and model simulated Arctic sea ice extent (a) and difference in ice extent between the model runs without (Model SEN) and with (Model CNTL) the August 2012 cyclone in the wind forcing (b) over 1 August – 25 September 2012. The dates marked with vertical lines show when the 2007 ice extent minimum record was first broken (August 26) and the time (September 16) of the minimum extent in 2012.

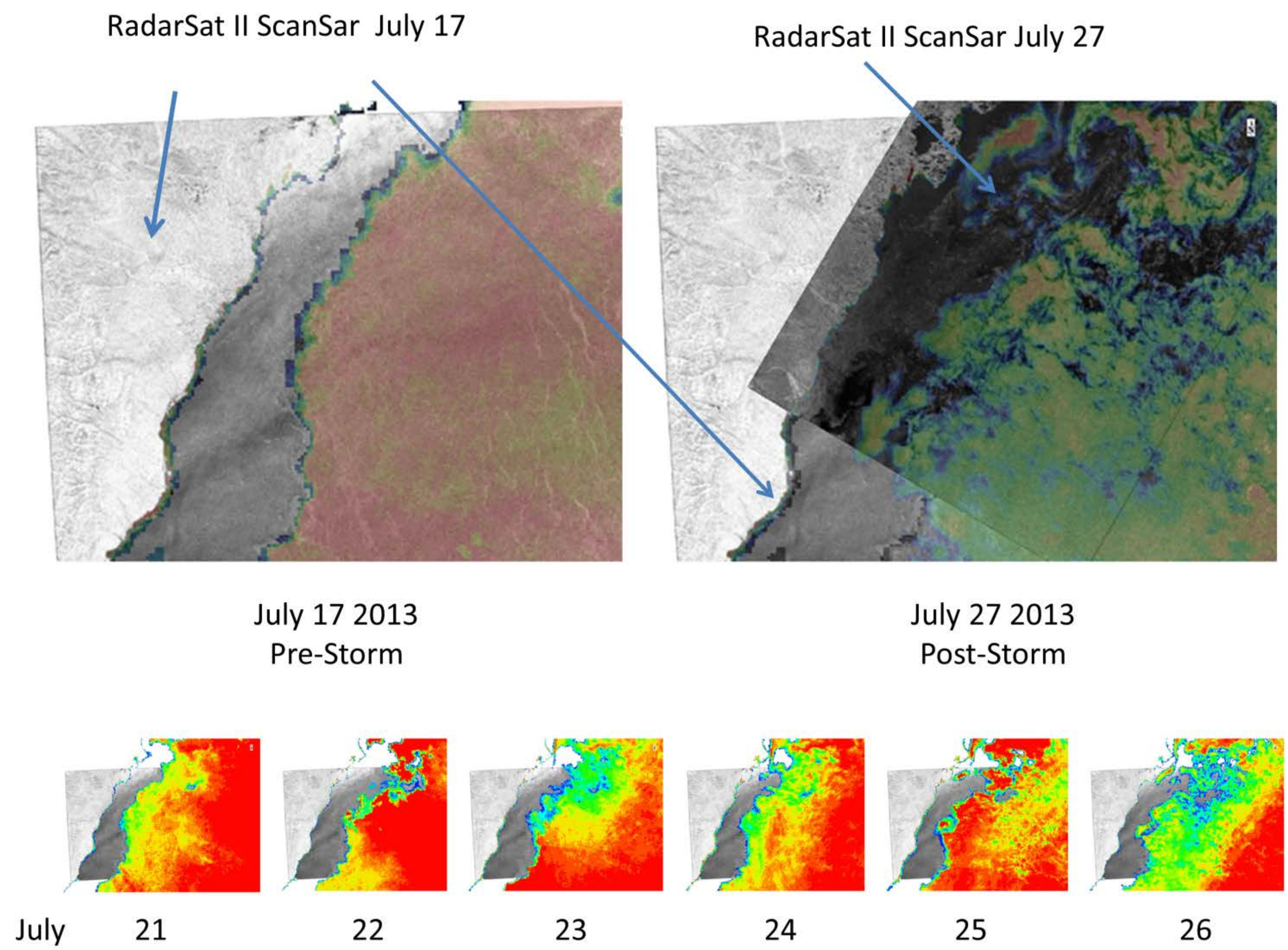

Figure 3. RadarSat II ScanSar images (50 m footprint) with 3.125 km passive microwave derived ice concentration from AMSR-2 (University of Hamburg) overlaid for July 17 and July 27 (top row). Note the sharp ice edge on July 17 depicted in both the SAR data and the passive microwave images. Over the course of the 10 days between those images the MIZ expanded dramatically. Bottom sequence: Evolution of MIZ during the passage of a storm from July 21 through July 27 from AMSR-2 passive microwave (University of Hamburg).

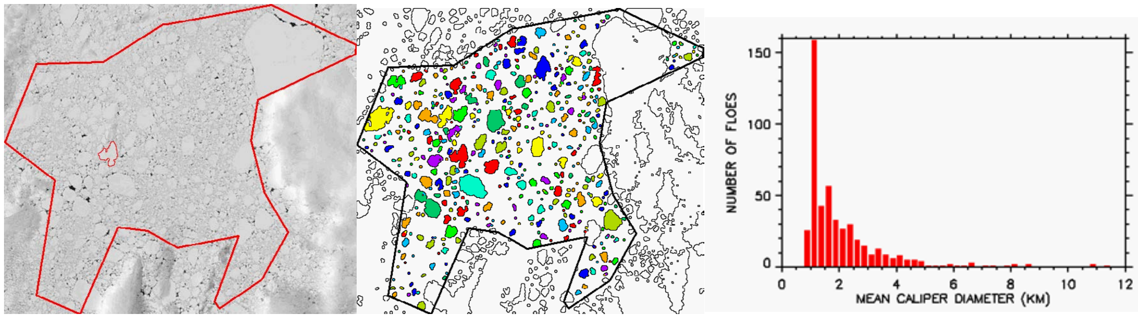

Figure 4. Left: MODIS image subset, band 3 (visible), from July 7, 2013, near 80°N 180°W, measuring 143 × 125 km (571 × 501 pixels). The heavy red outer curve is the boundary of the cloud-free region. The small red inner curve delineates one particular ice floe. Middle: Dilated labelled image. Floes are outlined in black. Only the colored floes, which fall completely within the cloud-free region, are used in the analysis of FSD. Right: floe size distribution based on MCD.

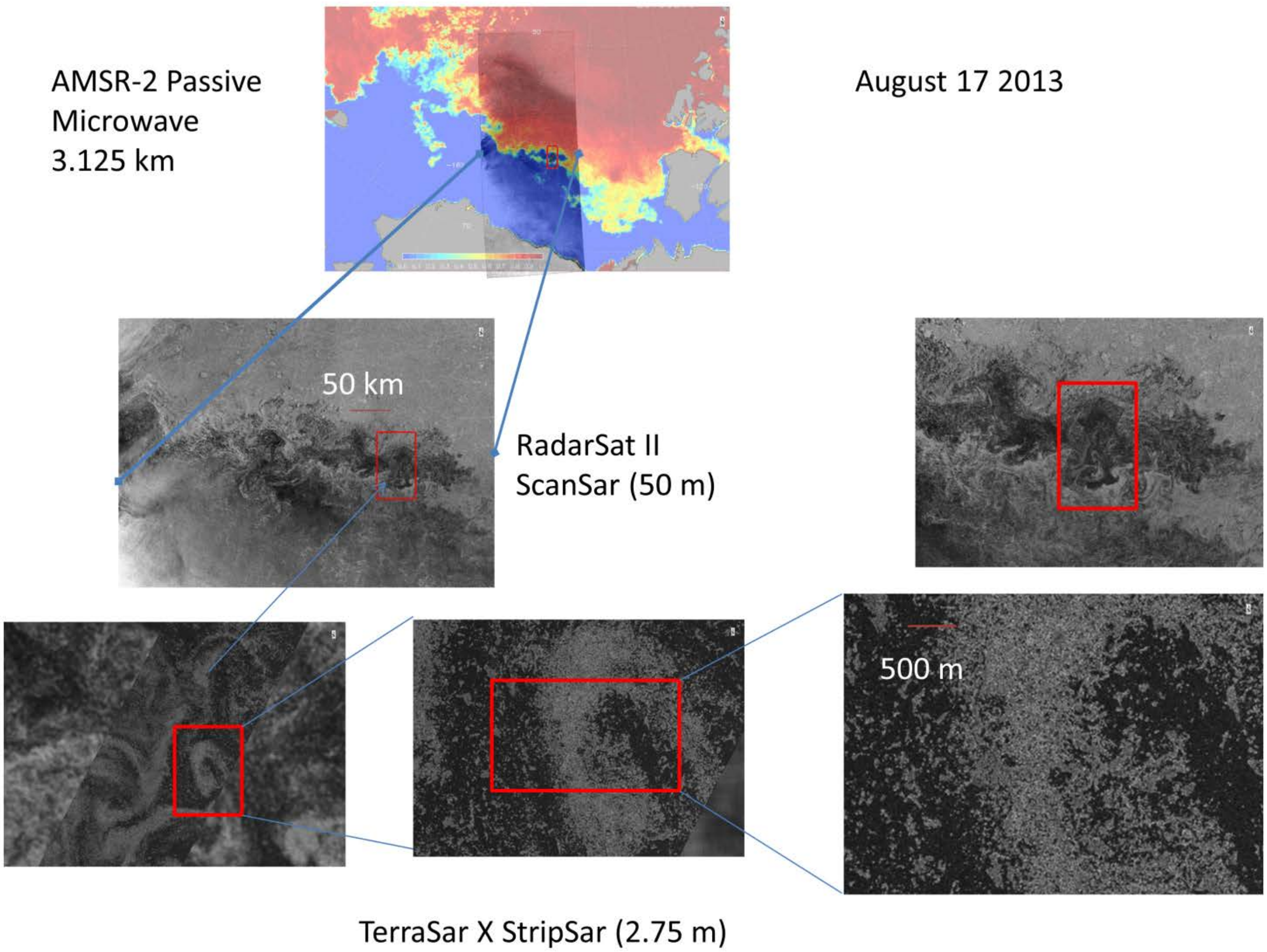

Figure 5. Top row: AMSR-2 passive microwave derived ice concentration (3.725 km footprint) for August 17 2013, with RadarSat II ScanSar image overlaid. Middle row: RadarSat II ScanSar image for area of detail indicated by blue lines (left), and greater detail with TeraSar X StripSar image (2.75 m footprint) overlaid (right). Bottom row: StripSar image at increasing (from left to right) detail corresponding to red boxes. Image on right shows StripSar image at full resolution showing small elongated ice floes. Area in the center of full resolution image may contain ice floes that are not resolved at this resolution.

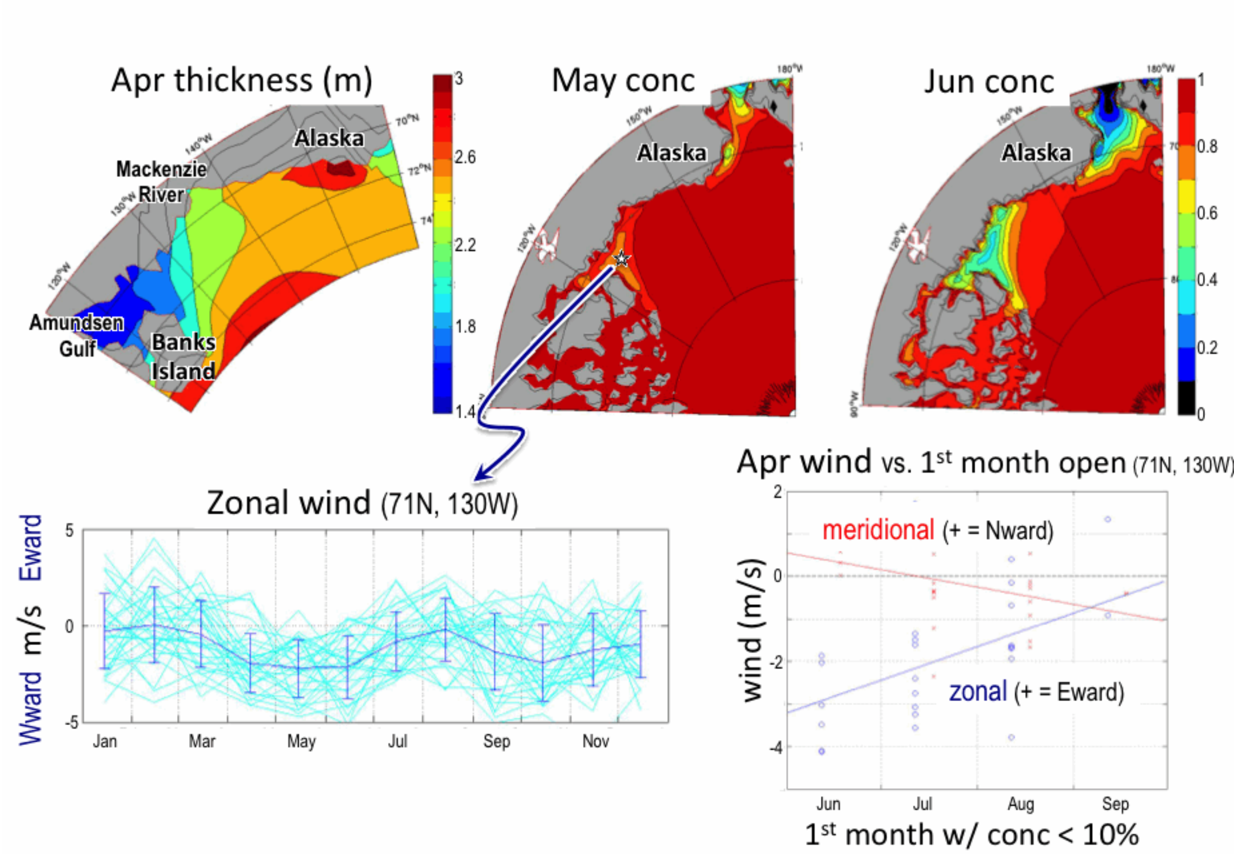

Figure 6. Analysis of early ice retreat in the southeastern Beaufort Sea. Upper left panel shows climatological April mean ice thickness from PIOMAS, just before the melt season. The next two upper panels show early ice retreat in this area, from NSIDC passive microwave (SSMI) monthly means. The bottom left panel shows zonal wind from NASA's MERRA reanalysis product (positive = eastward) at 71N, 130W (star symbol in May concentration figure above), with each year from 1979-2012 in cyan and the overall mean (plus/minus 1 standard deviation) in dark blue. The bottom right panel shows how April mean winds predict the 1st month when ice concentration drops below 10%.