SAR Motion Products: Tools for Monitoring Changes in Sea Ice Mass Balance and Thickness Distribution

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ABSTRACT: Sea ice is a discontinuous non-rigid material when viewed from microwave SAR imagery at scales of tens of kilometers. The discontinuous motion and behavior of sea ice has a definitive impact on its thickness distribution. Techniques for resolving sea ice discontinuities are demonstrated as contributions toward an integrated Arctic Observing Network.

1. INTRODUCTION

The sea ice community has basic knowledge of how the ice thickness distribution varies regionally and seasonally throughout the Arctic. The fraction of ridged ice varies between 10-30% in the Laptev Sea (mean end-of-winter thickness ranges between 2 to 3 m) [Haas and Eicken, 2001] and 40-80% in the convergent region north of the Canadian Archipelago [Melling et al., submitted] (mean end-of-winter ice thickness is between 6-8m). We also know that ice thickness has large decadal and interannual variability. For example, there is a decadal trend in multi-year ice thickness in the Beaufort Sea, with a decrease in thickness of 1.3m between the 1960/70s and 1990s [Rothrock et al., 1999]. This has been related to changes in ice circulation regimes in observational [Rigor et al., 2002] and modeling [Lindsay and Zhang, 2005] studies. There is pronounced interannual variability, O(1x106 km3), in Fram Strait ice export [Kwok et al., 2004]. Melling et al. [2005] found the interannual variability of ice thickness in the Beaufort Sea to be up to 2.7m. One cause of this variability is dynamic in nature, with changes in ice circulation resulting in (1) changes to the age of ice exiting the Arctic or entering a local region and (2) changes to the sea ice deformation rate.

Global Climate Model (GCM) projections of future ice extent show ice receding, and loss of the perennial ice zone, though models disagree on the rate of recession [ACIA, 2005]. Models used in the ACIA study all have very different constitutive models, thermodynamic models, and atmospheric dynamics. As the sensitivity of ice thickness to thermodynamic parameterizations, dynamic parameterizations, and ocean/wind forcing variability are comparable (e.g., Steele and Flato [1999]; Kreyscher et al. [2000]). Thus, it is not possible to isolate the cause of the differences using only models. One way to improve these models is to identify the magnitude and direction of feedbacks on the ice mass balance, and build accurate parameterizations of ocean-ice-atmosphere coupling.

We do not know whether dynamic effects result in negative or positive feedback to sea ice mass decrease in a warming climate. For example, in a weakening ice pack, we could expect convergence to increase as resistance to closure decreases. Hence the ice ridging rate could increase (a negative feedback). On the other hand, large scale changes in ice drift and increased surface wave activity, from an increase in fetch length, might result in less compression against the coast and multi-year ice zone, hence reducing the ridging height yet increasing the aerial coverage and potentially total new ice growth; a positive feedback mechanism. To determine the sign and magnitude of this feedback we must improve our understanding of how new ice grows and how ridging, and rafting will respond to such things as: (a) increasing storminess in the Arctic; (b) a seasonal ice pack of reduced thickness; and (c) large scale changes in drift modifying ice stress.

As we do not know whether current models adequately represent leads, we are uncertain of their ability to correctly represent observed sea ice strain rate and its impact on ice growth and redistribution. Models show that increasing deformation rates and variability result in increased total ice mass [Heil and Hibler, 2002; Kwok et al., 2003]. Yet, we lack quantitative validation of model estimates and the effect of deformation on ice mass. This is in part because the in situ data required for such validation is sparse and incomplete. As sea ice thickness is highly sensitive to modification of rheological and surface stress parameterizations, typically showing 10-20% sensitivity [Kreysher et al., 2000; Hutchings, 2001], it is very important to simulate the stress-strain rate relationships adequately.

In short, there is a need to improve our understanding of the interplay between ice dynamics and mass balance including necessary input for the design of an optimal set of observation methods for long-term monitoring of sea ice mass balance. This need addresses high priority research topics listed in recent program documents, including SIMBA [Hutchings and Bitz, 2005], SEARCH [SEARCH 2005], DAMOCLES (Gascard, pers. comm.), IPY [Perovich et al., 2005] and ACIA [ACIA, 2005]. To achieve the goals listed in these documents, a comprehensive set of sea ice measurements needs to be taken to develop and validate models of both thermodynamic and dynamic processes for sea ice, across all the scales over which dynamic and thermodynamic processes vary.

The SAR techniques described in this paper are important contributions to an optimal measurement network for Arctic-wide monitoring. Specifically we focus on integrating SAR products at the kilometer to regional scales for sea ice mass balance monitoring. This is the range where teams of scientists engage in localized coordinated programs involving models, remote sensing, and in situ measurements. It is important to understand the needs at this level, because these regional programs are essential and fundamental nodes of a large Arctic-wide monitoring network.

2. BASICS OF TECHNIQUE

The basic technique of sea ice motion rendering using SAR imagery stems from a method known as region based motion estimation (or correlation method), which is derived from a fundamental principle called optic flow. This process tries to find the closest match in local image intensity between two time-lagged images. This has been an active area of research in the computer vision community [e.g., Barron, 1994 and references therein] with sea ice motion products basically developed from these principles with some modification [e.g., Fily and Rothrock, 1987; Kwok et al., 1990; Li et al., 1998; Liu and Cavalieri, 1998]. Unfortunately, this type of motion estimation is plagued by a problem known as the “generalized aperture problem”, which represents the uncertainty principle in image analysis and additionally defines an upper bound on the possible accuracy in motion estimates [Kruger, 1996]. The main difficulty arises in determining the size of an analysis window. Smaller analysis windows lead to high resolution estimates of the underlying motion, but the estimates may be biased due to insufficient gradient variation within the window. On the other hand, larger analysis windows come with the possibility to linearize the complex variations in the underlying motion field [Kruger, 1996]. In an effort to strike a balance between the computational complexity of large analysis windows and the optimality of small analysis windows, most algorithms proposed in the literature handle the aperture problem using multiple image resolutions of a single image [Anandan 1989; Thomas, 2000] or applying scaling techniques to the full resolution image such as the wavelet method by Liu and Cavalieri [1998].

A suite of tools already exist to explore several aspects of sea ice including 8 motion products (ice displacement, vorticity, divergence, shear, ice age, thickness and backscatter histograms, and melt onset) from a Lagrangian perspective at a 10km by 10km grid and from an Eulerian perspective (all but melt onset) at a 12.5 km by 12.5 km grid [Kwok et al., 1995; Kwok et al., 1999; Kwok and Cunningham, 2002; http://www-radar.jpl.nasa.gov/rgps/products.html]. There are also 5 km motion products during the SHEBA period (1997-1998) and 22 km products from the CASES 2003-2004 experiments. In all these cases, the correlation method assumes a sea ice continuum which imposes a threshold on the motion product resolution (~5 km).

The technique here is essentially another variant of the many methods that already exist with a few added features. First, we make use of a SAR image as a complex microwave backscatter signal (i.e., there is both a magnitude/intensity and phase/direction to the backscatter signal). The Fourier transform of the SAR image's intensity renders both a magnitude and phase component of the intensity in the frequency domain. We refer to the correlation of the "whitened" frequency domain phase component of an image's intensity as image intensity phase correlation (IIPC) to distinguish it from the correlation of the phase of the complex signal received in a SAR satellite image [Thomas et al., 2004; 2005; Geiger et al., 2005]. This method is illumination invariant since the whitening filters perform the required signal normalization. The phase of the intensity is practical for this application because it is a powerful tool for isolating the boundaries of features. However, unlike normalized cross correlation, IIPC can be efficiently computed in Fourier space [Vernon, 2001; Foroosh, 2002 and references therein]. This provides the opportunity to utilize high-speed FFT methods to solve the motion in a computationally efficient manner. We handle the motion estimation process at multiple resolutions [Anandan, 1989] with the estimated information being percolated from coarse-to-fine resolutions based on a filtering of the image from its original resolution to more smoothed renditions.

As with all previous methods, we found that this processing method works well in regions where continuous motion exists. However, one sees clearly from SAR imagery that sea ice is not a continuous, material, so we need to refine our method to resolve regions of discontinuity [Vernon, 2001]. This fact arises from the Affine Fourier Theorem [Bracewell, 1993] where the linear motion approximation is considered correct only under the assumption that the magnitude of distortion is much smaller than the translational motion. We turn this constraint from a problem to a solution by identifying the poor results (i.e., low values of correlation) as potential regions of discontinuities. We represent such results using a grey-scale map of the correlation coefficient. Visual

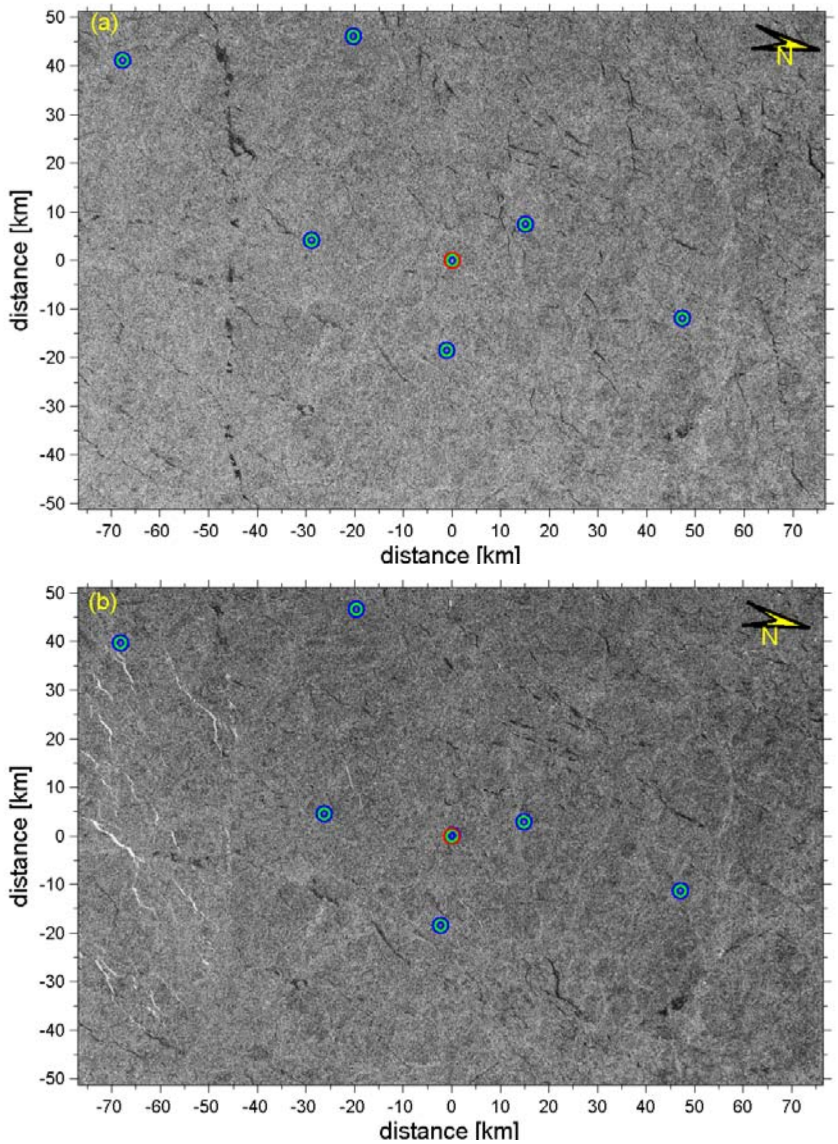

FIGURE 1. RADARSAT SAR images coincident with SHEBA buoys on multiyear sea ice floes. Shown are segments of RADARSAT SAR images (a) R110435256P3S013 and R110492261P3S013 on day 306 and (b) R110435256P3S013 and R110492261P3S013 on day 310 over the SHEBA research area in 1997. Coincident buoys (blue circles) and the drifting ship (red circle) are equipped with GPS units recording hourly position. Dark stripes are open water leads while bright white stripes are refrozen leads with very thin new ice.

inspection of such a correlation map reveals long linear features with distinctly different motion patterns on either side of the features. Making additional use of the velocity gradient observed across these regions, we are able to further refine and identify the discontinuities using a masking scheme to define regions of continuous versus discontinuous flow. In this way we are able to map a discontinuous material by defining boundaries of discontinuities, and then computing the velocity in the continuous regions where the Affine Fourier Theorem is valid. This technique is essential in our efforts to understand the behavior of sea ice as a discontinuous non-rigid material. A detailed description of this process from a geophysical perspective is described in Geiger et al., [2006].

3. RESULTS

As an example, Figure 1 shows SAR imagery segments in the vicinity of the SHEBA buoy array during the 1998 field season in the Beaufort Sea [Richter-Menge et al., 2002]. In particular, we direct the reader to the presence of short and long dark narrow features which delineate the ice into fragments or aggregates. Some of these delineations behave as slip lines along which aggregates plates of sea ice move. This is the basic composition of sea ice as a discontinuous material which we are trying to understand further. Figure 2 is an estimate of the motion of this region when resolved to the continuum resolution of 4.8 km. There is good agreement between the velocity derived from the buoy displacement and that of the SAR image as independent calculations of the motion (Figure 2). This is the typical product developed from SAR image processing methods and it provides a wealth of information about the large-scale motion of the region. However, there is more information to be gained from these images if one looks beyond the constraint of a continuum approximation.

The remote sensing products shown in Figure 3 incorporate a series of SAR ice motion analysis tools developed by Thomas, Geiger, and Kambhamettu [2004, 2005]. These new computational methods resolve the discontinuous non-rigid motion of sea ice [Geiger and Drinkwater, 2001; 2005; Thomas et al., 2004; 2005; Geiger et al., 2006]. This work is motivated by a need to provide SAR motion products as input and validation for lead-resolving sea ice models and to advance the understanding of fundamental sea ice processes and interactions. In particular, we are interested in the capabilities of this system to (1) aid in the deployment strategy of buoy arrays, (2) compute the mechanical thickness redistribution along 10 km and 100 km 1D strain rate transects coincident with GPS buoys and thickness measurements, and (3) provide high spatial resolution global and relative motion, and strain rate fields of divergence and shear over a regional research area (hundreds of kilometers). The approach distinguishes itself from existing efforts by assuming a priori that the image is from a discontinuous non-rigid material. By marking the discontinuities, a very high resolution product (as small as 400 m resolution) can be produced (Figure 3). This capability encourages us to make more detailed investigations between high temporal resolution ice drifting buoys and high spatial resolution all-weather SAR-based motion products with the hope of developing an effective synthesis from a combination of these two data sets.

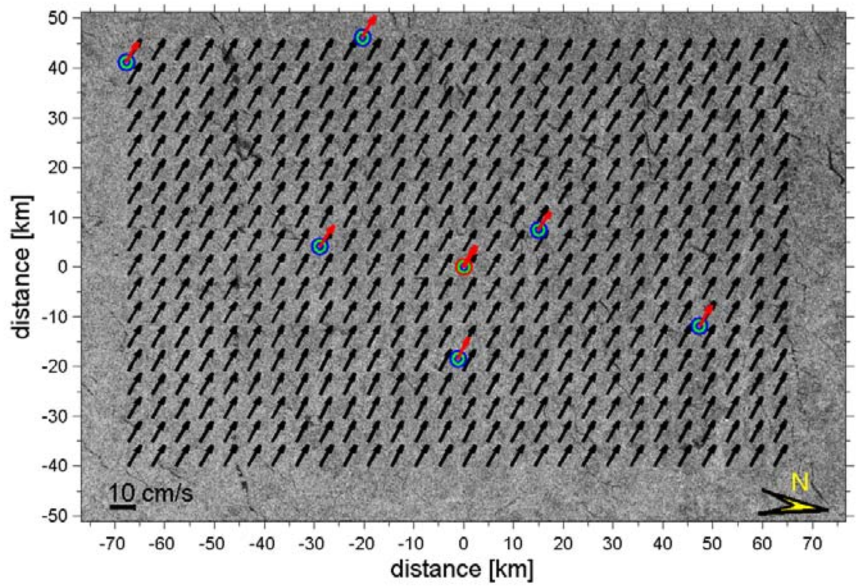

FIGURE 2. Standard motion products. The SAR scenes and buoy positions from Figure 1 are used to compute velocity vectors to a resolution of 4.8 km which is close to the smallest reasonable continuum scale. Buoy motion vectors (red) are computed from the buoy positions at times corresponding to the SAR scenes for independent comparison of motion products.

4. CORRELATIONS WITH OTHER TECHNIQUES

Figure 5 in Thomas et al. [2004] shows the scatter map from 12 ERS-1 image pairs from the Weddell Sea (a particularly difficult region to track sea ice motion). When compared with the 2650 motion vectors rendered from those images by Drinkwater [1998a, b], 72.8% of the estimated motion vectors were within a 400 m displacement difference. We choose this threshold because of the SAR geolocation uncertainty of 323 m described by Holt et al. [1992]. We can account for 93.5% of all the data points when we identify remaining flagged points in discontinuous regions (which do not compare to within 400 m using continuum-based methods because of the discontinuities). The remaining 6.5% of data are displacement results greater than 400 m which we can not account for using a correlation map and velocity gradient demarcation scheme. These points correspond to regions where the gradient of the velocity is high but the correlation is not low (infinitesimal discontinuities relative to image resolution) which, in principle, requires a higher-order motion model to localize the position of a potential discontinuity. Hence, initial comparisons with other SAR motion products yields encouraging results and accuracies to within the measuring capabilities of the SAR instrument itself. However, for an independent measurement, we require a comparison against in situ measurements of sufficiently high density to test the location and motion of sea ice discontinuity features. We currently seek such opportunities to test our methodology further.

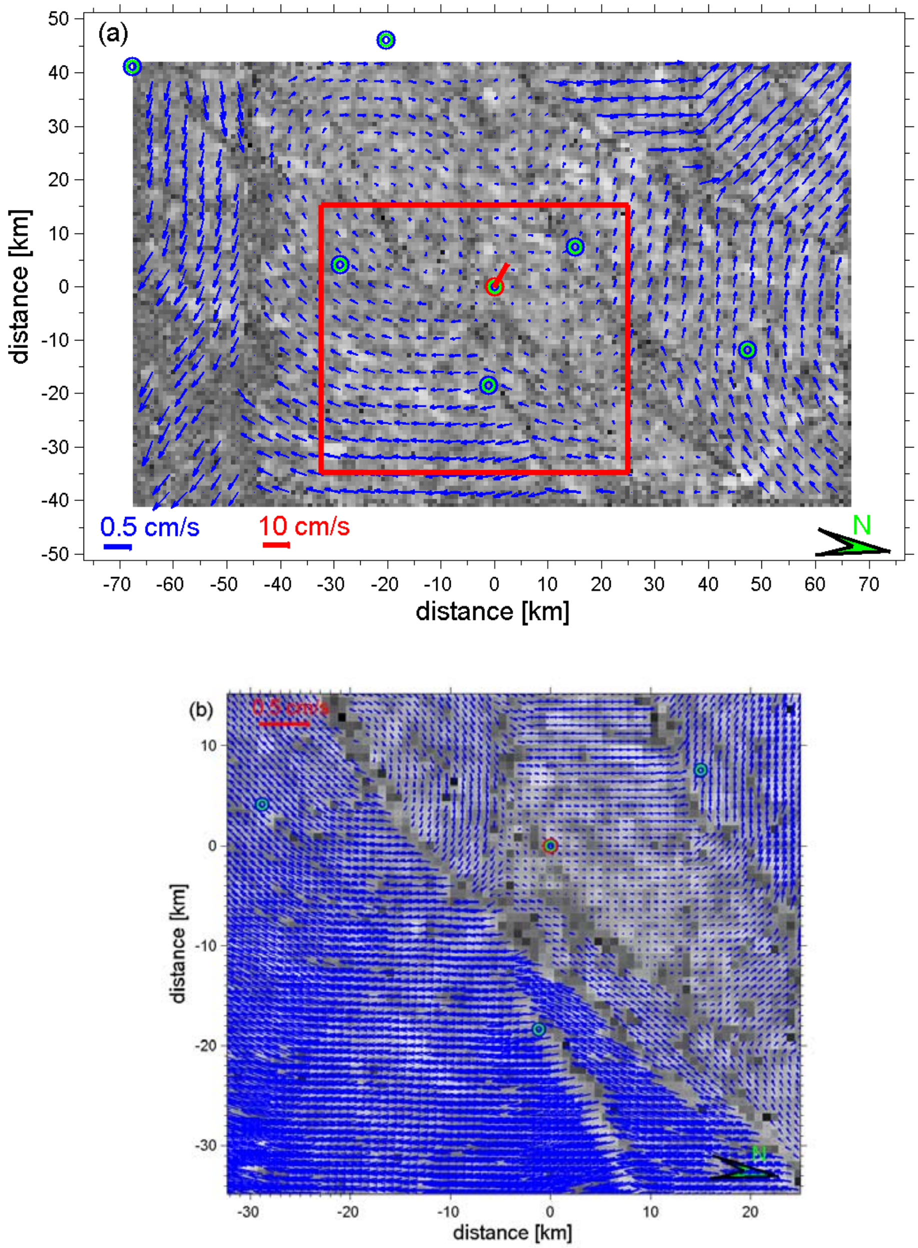

FIGURE 3. Sea ice mesoscale structure. Global motion is shown for the ship (red vector) with relative motion shown at all other points (blue vectors). This representation displays both global and local motion and illustrates the discontinuous behavior of sea ice as a material (low correlation, as likely discontinuities, are notated by the darker shaded boxes). Detailed flow structure within individual continuous regimes as seen in (b) referenced from the red box in (a). Every 4th vector shown in (a) while every vector (400m resolution) shown in (b). Despite their close distances, the buoys are located within different aggregates separated by shear zones, leads, and ridges. There is a clock-wise (anticyclonic) eddy-scale circulation resolved in a fractured form in the upper left. Ice-ice interactions due to aggregate plate dynamics modify the ice circulation pattern away from a smoothly varying continuum.

5. RECOMMENDATIONS & CONCLUSIONS

The method identified in this paper requires further validation using independent sources especially in the confirmation of discontinuity location and local-motion accuracy. We currently seek means to test this method, especially opportunities to compare such results with high-density buoy deployment programs. We also seek to understand and validate this method in the context of sea ice thickness distribution, so as to combine a buoy-SAR program with sea ice thickness observations to validate the location of leads and ridges found in the method presented here. Such testing also provides an incredible opportunity to combine all three recently evolved technologies (GPS buoys, new SAR processing techniques, and new ice thickness instrumentation) to explore the behavior of sea ice at the regional scale in a way that has never been possible before.

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