Sea Ice Kinematics and Surface Properties from RADARSAT SAR During the SHEBA Drift

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Submitted to JGR Oceans for the SHEBA Special Section
May 31, 2000

Abstract

Satellite data are important for providing the large-scale context of the SHEBA station and for characterizing the spatial variability of the sea ice in its vicinity. The Canadian RADARSAT satellite collected 195 synthetic aperture radar (SAR) images of the SHEBA site over the course of the one-year drift. The RADARSAT Geophysical Processor System (RGPS) used these images to compute the spatial pattern of ice motion within 100 km of the SHEBA station by tracking features in sequential images. From the ice motion data, the divergence and shear of the pack ice are estimated. The divergence is large from November to January, followed by a gradual convergence from February through July. The character of the ice motion changes at the end of July, from piecewise rigid motion to free drift. The ice motion reverts to its winter-like character in late September. Thus the "kinematic" summer runs from late July to late September. The radar backscatter also goes through seasonal transitions, capturing the abrupt onset of melt (May 29) and freeze-up (August 15). The concentration of multiyear ice is about 94% in the fall, and its backscatter signature remains stable through spring. Multiyear and first-year ice cannot be distinguished during the summer melt season, and the mean backscatter is inversely correlated with the surface air temperature. The "thermodynamic" summer runs from late May to mid-August.

1. Introduction

One of the purposes of the SHEBA (Surface Heat Budget of the Arctic Ocean) drift phase, from October 1997 to October 1998, was to make measurements of the ocean, atmosphere, and sea ice properties that could then be used to improve parameterizations of processes in single-column models of Arctic air-sea-ice interaction. The ultimate goal is to "scale up" the single-column models and results to improve basin-wide simulations of Arctic climate and its interaction with the global climate [Moritz and Perovich, 1996]. Remote sensing data are essential for characterizing the local and basin-wide properties of the sea ice and their variability so that proper "scaling up" can be accomplished.

This paper describes a unique remote sensing data set and two areas of application: sea ice motion and deformation, and the evolution of sea ice surface properties. The Canadian RADARSAT satellite collected 195 synthetic aperture radar (SAR) images of the SHEBA site between November 1, 1997, and October 8, 1998, or roughly one image every one to three days. The C-band (5.3 GHz) RADARSAT SAR imaged a swath on the earth 460 km wide (in ScanSAR mode) with a pixel size of 50 m, unhampered by clouds or darkness. The satellite data were received and processed into imagery at the Alaska SAR Facility (ASF) in Fairbanks.
Sequential pairs of images were then processed by the RADARSAT Geophysical Processor System (RGPS) at the Jet Propulsion Laboratory (JPL) in Pasadena to derive the motion of the sea ice on a 5-km grid by tracking common features in each pair of images. Thus we have a year-long record of the spatial pattern of ice motion and the radar backscatter in the vicinity of the SHEBA site.

Animation of the sequence of images reveals for the first time the details of sea ice motion in time-lapse fashion. Large "plates" of ice (~100 km or more) are seen to slide past one another; leads open and new ice forms in them; leads close and bright pressure ridges appear; dramatic seasonal transitions are marked by large jumps in radar backscatter. These events have been seen before in isolation, but not in a time series following a single location through a whole annual cycle.

Several research projects are making use of this data set. Work is underway to relate the large-scale discontinuous plate motion to the continuous wind forcing [Moritz and Stern, in prep.]. The ice motion computed by RGPS has been used to drive a granular model of sea ice [Hopkins, 1999]. The ice divergence computed from the RGPS ice motion grids has been used to drive a single-column ice thickness model [Curry et al., 2000]. The strain rates have also been used in a study relating Arctic pack ice stress and deformation [Richter-Menge et al., 2000], and in a study of rafting and redistribution of ice thickness [Babko, 2000]. The ice motion data are being used in a data fusion study to derive the best estimate of ice deformation near SHEBA [Lindsay, 2000]. Other potential applications include the study of lead patterns, the testing of anisotropic constitutive models of sea ice [e.g., Hibler and Schulson, 2000], investigation of the information content of SAR images [e.g., Kerman et al., 1999], and comparisons with surface measurements that could correlate with changes in radar backscatter.

After describing the data sets and derived products, we present some results from the analysis of the ice deformation and the time series of radar backscatter. The kinematic and radiometric analyses reveal different regimes and seasonal transitions in the sea ice. The final section contains conclusions and remarks about other relevant RGPS data sets.

2. Data Sets

2.1 Imagery

The frequent RADARSAT coverage of the SHEBA site is due to NASA’s RGPS project. The data acquisition plan for RGPS calls for imaging the entire Arctic basin every three days (the "Arctic Snapshot"). The total U.S. allocation for RADARSAT data is limited, but the SHEBA site fell within the domain of the Snapshot, so images were acquired regularly without additional planning by the SHEBA Project Office and without additional use of the U.S. allocation.

The 195 images produced by ASF are geocoded to the SSM/I polar stereographic projection, with standard parallel at 70°N latitude and +X axis along 45°E longitude. Included with the images are calibration coefficients that allow pixel values to be converted to normalized radar backscatter. The pixel size is 50 m and each image is approximately 230 megabytes in size.
To reduce the size and complexity of the image data and enhance their usefulness, we first applied the calibration coefficients (with software from ASF) to convert pixel values to radar backscatter, and then extracted two sub-images from each calibrated image. Both sub-images are centered on the SHEBA station. One is 40 x 40 km in extent and retains the original pixel size of 50 m; the other is 200 x 200 km in extent and has a pixel size of 250 m (5 x 5 block averaging and sub-sampling). The SHEBA station was identified in each original image by a manual procedure in which the known daily position of the ship was first used to display a sub-image of the approximate station location. The operator then selected the exact pixel at the center of the station, which almost always showed up as a small bright (high backscatter) cluster of pixels. The manually selected pixel location became the center of the extracted sub-images. Ensuring that the SHEBA station is at the center of each sub-image allows the animated sequence of sub-images to show changes in surface features relative to the station.

Figure 1 shows the geographical location of two RADARSAT image frames, from January 10 and 11, 1998. The SHEBA drift track is also shown, with the position on January 11 marked by a small dot (75°N 150°E). Centered on that position are the two sub-image frames, 40 x 40 km square and 200 x 200 km square. Figure 2 shows the SAR image of January 11; the yellow box measures 40 x 40 km and is centered on the SHEBA station. Figure 3 shows the SAR image within that box; the station is at the center of the yellow circle. (The red and green grid lines are explained in section 2.3 below).

2.2 Ice Motion

The RADARSAT Geophysical Processor System, funded by NASA and developed at JPL, computes sea ice motion, deformation, and thickness throughout the Arctic basin by following small Lagrangian cells in sequential RADARSAT SAR images [Kwok et al., 1995]. For the purposes of the SHEBA drift, the RGPS team at JPL created a special data set consisting of ice motion on a 5-km grid, 200 x 200 km in extent, and centered on the SHEBA station. The ice-tracking algorithm uses cross-correlation to automatically identify common features in pairs of SAR images [Kwok et al., 1990]. The SHEBA ice motion data set is Eulerian: a new, regular 5-km grid is initialized on the first image of each sequential pair, and the grid points are tracked to the second image of the pair. A new grid is then initialized on that image for the purpose of tracking to the subsequent image. Particles of ice are not followed in a Lagrangian fashion through a long sequence of images. However, each newly initialized grid is centered on the SHEBA station as it drifts across the Arctic Ocean.

There are 184 sets of ice motion data for the SHEBA drift, each one spanning (typically) a one to three day period. (The ice could not be tracked in every single pair of the 195 images). The longest data gap is 16 days, from December 25, 1997, to January 10, 1998. The spatial extent of each ice motion product ranges from the full 200 x 200 km to only tens of kilometers in some summer cases where the tracking proved to be difficult due to surface features becoming "washed out". Also, when the SHEBA station happened to fall within 100 km of the edge of an image, the full 200 x 200 km grid could not be tracked.

There are two sources of errors in determining the ice motion from sequential images: geolocation errors and tracking errors [Holt et al., 1992]. The first refers to the uncertainty in the
geographical location of each pixel. The second refers to mistaken identification of corresponding pixels by the ice-tracking algorithm. These errors are uncorrelated with each other, and both are small in the present data set, on the order of 100 to 200 m. This leads to an uncertainty in each ice displacement vector of about 200 m (independent of the time interval over which the displacement occurs), which is at least as accurate as displacements obtained from drifting buoys [Lindsay et al., 2000]. The uncertainty is much smaller than the mean displacement of 11 km for the 184 ice motion data sets. Only five of the 184 have a mean displacement less than 1 km.

Ice motion fields are typically displayed with vectors. In Figure 2 we display instead the configuration of the grid on January 11 that originally consisted of regular 5-km squares on January 10. Those grid cells that have remained square are shown in red. The ones that have deformed (by more than 15%) are shown in green. The pattern of deformation is discussed in 3.2 below. Figure 3, the 40 x 40 km sub-image of January 11, also shows the correspondence between the deforming (green) cells and certain leads in the SAR image.

2.3 Derived Products

Knowledge of the ice motion on a regular grid allows one to estimate its spatial gradients, i.e. strain or strain rate. Let \((u,v)\) represent the ice velocity at location \((x,y)\). We estimate \(u_x\) (partial derivative) and the other three partial derivatives for each 5-km cell using standard finite difference formulas. Values for individual cells can then be averaged together to obtain larger-scale strain rates, if desired. We combine these (whether averaged or not) into the strain rate invariants, divergence \((D = u_x + v_y)\) and shear \((S = \sqrt{(u_x - v_y)^2 + (u_y + v_x)^2})\). The magnitude of the strain rate is given by \(|\varepsilon| = \sqrt{D^2 + S^2}\). The procedure is the same as that used by Stern et al. [1995] with ice motion data derived from ERS-1 SAR images by the predecessor of the RGPS. The result is a time series of 184 values of \(D, S, |\varepsilon|\) (if strain rates have been spatially averaged) or 184 spatial patterns of \(D, S, |\varepsilon|\) (if no spatial averaging). For example, Figure 4 shows the time series of ice divergence \((D)\) in the vicinity of the SHEBA station, computed at four different spatial scales (averaging sizes) centered on the station. Figure 5 shows the spatial pattern of \(|\varepsilon|\) over 12 time intervals in which each 5-km square is color-coded according to the size of \(|\varepsilon|\). These are discussed in section 3.2 below.

3. Kinematic Analysis

3.1 Ice Motion

The dominant driving force on the sea ice is the wind. A complex regression of the year-long record of daily ice drift (from GPS) on the 10-meter wind measured at the SHEBA station gives a squared correlation of 0.85, with the ice moving at 2% of the wind speed and 29 degrees to the right of the wind vector. A seasonal analysis gives a squared correlation of 0.88 in winter, 0.79 in spring, and 0.92 in summer and fall.
It is also known that the ice undergoes small inertial motions due to the rotation of the earth. This can lead to aliasing of the ice velocity if the position of the ice is not measured over an integral number of inertial periods. Fortunately the RADARSAT overpass time for 190 of the 195 images only varies by plus-or-minus one hour (around 18:00 GMT), so the time intervals between images are close to multiples of the inertial period.

Besides the general drift of the ice indicated by the trajectory in Figure 1, observations of ice motion from this data set (such as Figure 2) and other data sets clearly indicate that the winter ice cover consists of large rigid plates that move relative to one another along linear "cracks". The value of the RGPS ice motion data sets is in the detailed spatial patterns of this differential ice motion, or deformation, around the SHEBA site.

3.2 Ice Deformation

Sea ice deformation drives changes in the ice thickness distribution through the creation of leads where new ice can grow, and through the creation of pressure ridges, which contain one third of the mass of Arctic sea ice. Therefore characterizing the deformation is important for understanding the mass balance of the ice cover.

The time series of ice divergence around the SHEBA site (Figure 4) shows an interesting annual cycle. In the fall and early winter, as the pack ice is growing and strengthening, the divergence is mainly positive (new leads form, new ice grows). All four spatial scales in Figure 4, from 50 to 200 km, indicate a cumulative divergence of about 25% between November 1 and December 25. January contains large divergent and convergent events. Throughout most of the month the wind speed is moderate (~5 m/s) and the direction varies from northerly to easterly. The ice drifts westward as leads form with a generally northwest-southeast orientation. At the end of January the wind speed picks up quickly (14 m/s on January 26) and the direction shifts to slightly south of easterly. This causes a large convergence of ice as the new leads that formed earlier in the month are forced to close and ridge [Richter-Menge et al., 2000]. Then, from early February until the end of July, the divergent and convergent events are small, but the pack ice undergoes a gradual convergence of about 15% as the SHEBA station drifts within the Beaufort Gyre (see the surface air pressure patterns derived from drifting buoys in Rigor and Ortmeyer, 1999). The gradual convergence persists beyond the onset of summer melt (May 29), which marks a thermodynamic change but not a dynamic change.

Throughout June and July, as the air temperature hovers around 0°C, the ice cover is melting and weakening. At the end of July a big storm blows through – the wind speed jumps from 4 to 10 m/s on July 27-29 and the wind direction shifts from southerly to westerly. This gives rise to the large divergence seen in Figure 4 in late July and early August. But it also marks a change in the character of the ice deformation. The winter pattern typically consists of large rigid areas of ice (plates) crossed by linear actively deforming zones (cracks), as in Figure 2. After July 28, however, the nature of the deformation changes to a more random pattern consistent with free drift conditions and low ice strength. Figure 5 illustrates the transition. The panels show the pattern of the magnitude of the ice strain, |ε|, over 12 time intervals from Days 196-197 (July 15-16) to Days 213-214 (August 1-2). The SHEBA station is at the center of each 200 x 200 km
panel, and each 5-km cell is color-coded according to $|\varepsilon|$ for that cell, from blue ($|\varepsilon| = 0$) through the spectrum to red ($|\varepsilon| > 0.25$). The pattern of $|\varepsilon|$ for Days 199-202 (July 18-21) shows winter characteristics: linear cracks (red) and plates (blue). This is followed by a week of almost no deformation activity, which ends with the storm of July 28 (Day 209). The pattern of $|\varepsilon|$ after that date is markedly different (bottom four panels). The deforming zones are in clumps rather than lines, and the distribution of $|\varepsilon|$ is more even, i.e. less dominated by purely rigid (blue) and highly deforming (red) cells. The amorphous character of the deformation pattern persists through September 11 and then enters a three-week transition period, after which it re-acquires the winter-like properties of plates and linear cracks (not shown). This fall transition period coincides with a three-week interval when the surface (2 m) air temperature goes through four oscillations between -2°C and -8°C before plummeting to -22°C on October 4. Clearly the leads and open water were gradually freezing up during the transition period, diminishing the freedom of the ice floes to drift independently. The pack ice became well consolidated by October 4. The time series of divergence (Figure 4) allows the same interpretation: there are large excursions from the end of July to mid-September during free drift, followed by a return to fall conditions (consolidated pack, moderate positive divergence) after late September.

The qualitative similarity between the four panels of Figure 4 suggests that the same events contributing to the divergence of the ice within 50 km of the SHEBA station also extend out to a scale of at least 200 km. The seasonal contributions to the divergence at the 100-200 km scale are roughly as follows: +25% in November and December, +5% in January, −15% from February through July, and −6% in late summer and early fall. This gives a net annual divergence on the order of +5%. However, at the 50 km scale the big convergent event in January dominates the divergent event, and the late summer convergence is also larger, so the net annual divergence is about −10%.

The shear deformation ($S$) is much larger than divergence ($D$), as is usually the case. While the ice was diverging at about 0.4%/day in the fall and early winter (all scales), the shear rate was ~2%/day at the 200 km scale and 3%/day at the 50 km scale. The shear deformation peaked in January (4-6%/day), was relatively low throughout the winter, spring, and early summer (~1.5%/day), and picked up again in late summer and early fall (3-4%/day). During the cold season, shearing of the ice can create open water where new ice can grow [e.g., Stern et al., 1995]. Thus shear deformation must be taken into account in modelling ice production and ridging.

4. Radiometric Analysis

4.1 Seasonal Characteristics

The normalized radar cross section ("backscatter" or $\sigma^0$) is the ratio of backscattered power to incident power at the target location, expressed either as a dimensionless ratio or in decibels ($10\log(\sigma^0)$). The backscatter from sea ice results from a combination of surface scattering and volume scattering, depending on such properties as the surface roughness and the brine volume. Dry snow is nearly transparent to C-band (5.3 GHz) SAR, but the presence of even a small
fraction of liquid water greatly diminishes the backscatter. A smooth surface such as calm water or new undeformed ice has a low backscatter, whereas wind-roughened water or deformed ice has a higher backscatter. See Hallikainen and Winebrenner [1992] for more details.

The calibration accuracy of the RADARSAT ScanSAR imagery is described in Martyn et al. [1999]. The relative radiometric error within an image is 0.2 dB, and the relative error from image to image is 0.1 dB. The absolute radiometric error is 0.2 dB.

Figure 6 illustrates the well-known linear relationship in SAR imagery between the mean backscatter and the standard deviation. Each symbol represents one 40 x 40 km sub-image with a pixel size of 50 m, hence 800 x 800 = 640,000 pixels. Before the mean and standard deviation are computed, the central 7 x 7 pixels containing the (high backscatter) SHEBA station are deleted. In some cases the edge of the satellite swath cuts across the sub-image, reducing the number of pixels with image data, but in only 12 cases is the number of pixels less than 600,000. The linear relationship between the mean and standard deviation changes with season: winter and spring (January 10 to June 7, 1998) show a larger standard deviation relative to the mean than fall and summer (November 1 to December 25, 1997, and June 8 to October 8, 1998). The slope of the line through the winter/spring points is 0.55 with squared correlation 0.97. The slope of the line through the fall and summer points is 0.42 with squared correlation 0.94. The different slopes could be due to different mixes of ice types (see section 4.2 below) that alter the average scattering properties of the ice.

The backscatter from most surface types, including sea ice, generally decreases with increasing incidence angle. Figure 7 shows the relationship for the 40 x 40 km sub-images from fall (November 1 to December 25, 1997) and winter/spring (January 10 to May 28, 1998). For each sub-image the center incidence angle (at the SHEBA station) is used. The slope of the line through the fall points is −0.14 dB/degree with squared correlation 0.93. The slope of the line through the winter/spring points is −0.13 dB/degree with squared correlation 0.92. The incidence angle across each full ScanSAR image (460 km wide) ranges from 19° to 46°, but within each 40-km wide sub-image it varies by no more than ±1.2° from the center value, which translates into ±0.17 dB (using a slope of 0.14 dB/degree). This is less than the relative radiometric error within an image, hence the incidence angle can be considered nearly constant within each 40-km sub-image. The drop in backscatter from fall to winter/spring is due to a larger fraction of low-backscatter leads in winter/spring (see section 4.2 below), starting with the large divergent event in January (Figure 4).

Figure 8 shows the mean backscatter vs. time for the 40 x 40 km sub-images. The high frequency variations are due to the incidence angle effect: if the SHEBA station happens to lie in the near-range of the full ScanSAR image (closer to 20° incidence angle) then the backscatter within the sub-image is relatively high; if the SHEBA station lies in the far-range (closer to 45° incidence angle) then the backscatter is relatively low. The heavy line is not a running average – it is an adjustment of the mean backscatter to a standard incidence angle of 32.5°, using an adjustment factor (slope) of 0.135 dB/degree. Notice how stable the winter backscatter is – the temporal standard deviation of the 63 mean backscatter values from January 10 to May 28 is just
0.29 dB. Kwok and Cunningham [1994] noted the stability of the winter multiyear ice and first-year ice backscatter signatures in ERS-1 SAR images of the Beaufort Sea. The mean backscatter plotted in Figure 8 contains contributions from a variety of ice types, but multiyear ice is the dominant component, as we subsequently demonstrate.

The onset of summer melt and fall freeze-up are evident in Figure 8 and Figure 9 (dotted vertical lines at days 149 and 227). The 2-meter air temperature in Figure 9 has been interpolated from daily values (obtained from the SHEBA Project Office) to the times of the SAR images. On May 29 (day 149) the air temperature rose above 0°C for the first time and rain fell. This saturated the surface with water and the mean backscatter dropped by 2.5 dB in one day (compare to the gradual drop of 0.5 dB over the previous two months). On August 14 (day 226) the air temperature fell below −1°C and this triggered a jump of 4 dB in the mean backscatter (August 12-15) as the remaining liquid water on the surface froze. The temperature stayed below zero except for one brief excursion on August 22, and the mean backscatter stabilized at −11.5 dB (Figure 9, lower curve, right scale). Winebrenner et al. [1994 and 1996] used the changes in ERS-1 SAR backscatter of multiyear ice to make maps of the dates of melt onset and freeze-up in the Beaufort and Chukchi Seas. This technique can be used to measure the length of the melt season throughout the Arctic with RADARSAT SAR, and the RGPS will make such calculations [RGPS Science Working Group Meeting, February 2000].

The backscatter is very sensitive to the presence of liquid water on the surface, which in turn is very sensitive to the fluctuations in air temperature around 0°C. In Figure 9 the dips in temperature around days 163, 177, 214, and 220 (June 14, June 28, August 2, and August 8) are all accompanied by peaks in the backscatter of at least 2 dB above the background level. The correlation between air temperature and mean backscatter from May 29 (after melt onset) to August 12 (before freeze-up) is −0.57. The strong influence of the air temperature on the backscatter during the melt season explains why it is difficult or impossible to distinguish different ice types in the summer SAR imagery.

4.2 Ice Types

While each of the 40 x 40 km sub-images is centered on the SHEBA station as it drifts in the Arctic Ocean, the images are not strictly Lagrangian patches of sea ice – small amounts of ice are advected in and out of the 40-km frames over time, altering the mix of ice types and backscatter signatures. In order to follow the evolution of the same patches of ice over time, we selected one region of multiyear ice and one region of lead ice that were clearly identifiable throughout the entire fall/winter/spring (for the multiyear ice) or winter/spring (for the lead ice). The multiyear patch contains about 4500 pixels and is located in Figure 3 about 7 km "left" (west) of the station location at the center; the lead ice patch contains about 500 pixels and is located about 7 km "right" (east) of the station. Figure 10 shows the time series of mean backscatter (adjusted to 32.5° incidence angle) for the two patches of ice. Although the backscatter of multiyear ice is relatively stable, it does decay at an increasing rate from January to the onset of melt at the end of May. While it is likely that the final week of this decay is due to the rising temperature (−9°C to 0°C from May 22 to 29) and hence rapidly changing dielectric properties of the ice, the earlier portion of the decay is not directly attributable to temperature
effects. (One explanation might be a gradual decrease in the volume of scatterers in the bubbly upper layer of the ice as it ages). The backscatter of the lead ice plotted in Figure 10 is even higher than that of the multiyear ice on January 11 (see Figure 3), but drops to −15 dB on January 13 and then plummets to −21 dB over the next three weeks. This illustrates both the large separation between first-year ice and multiyear ice that prevails most of the time, and the potential for mis-classification during the early stages of ice growth, when such phenomena as frost flowers can temporarily brighten the surface of a new lead [Hallikainen and Winebrenner, 1992]. Notice that the decrease in the multiyear backscatter and the increase in the first-year backscatter in the springtime are compensating trends that have a stabilizing effect on the mean backscatter (see Figure 8).

The mean backscatter of multiyear ice in Figure 10 can be used as the basis of a simple classification procedure. First we fit a quartic polynomial to the multiyear time series. This captures the long-term seasonal trend without any short-term fluctuations. Then we assign a threshold for multiyear ice by subtracting a constant "buffer" from the polynomial. Every pixel with backscatter above the threshold is classified as multiyear ice. What is the proper buffer to subtract? Clearly the fraction of multiyear ice will increase as the buffer increases. The standard deviation of the multiyear backscatter is about 1.5 dB. Thus a buffer of 3 dB would set the threshold two standard deviations below the mean. The RGPS classification algorithm uses a buffer of 3.5 dB [Ron Kwok, personal communication]. In Figure 11 we plot the multiyear ice concentration (left scale) for three buffers: 3.0 dB, 3.5 dB, and 4.0 dB. The multiyear ice concentration starts at 94% (using the 3.5 dB buffer) in the fall (November 1), reaches a minimum of 61% at the end of January (see the large divergence in Figure 4), rebounds to 70% in early February, and then gradually increases back to 83% by the onset of melt (May 29). Of course the SAR sub-images that follow the SHEBA station are not true Lagrangian elements (as already noted) – ice does advect in and out of the 40-km frames. In fact, using the RGPS ice motion data we compute a net convergence of 12% at the 50-km scale from early February to the onset of melt, compared to an increase of 13% in the multiyear ice concentration over the same period. This suggests that multiyear ice advects into the 40-km image frames and replaces first-year ice as leads close.

We also identified a region of open water or new ice in a lead that developed on January 17, 18, 20, and 21. The mean backscatter in this 1000-pixel region (2.5 km²) was between −23.4 dB and −23.9 dB (adjusted to 32.5° incidence angle) on all four days, with a standard deviation ranging from 0.5 to 2 dB. Based on this, we assigned pixels to the open water / new ice category if their backscatter was less than −23 dB. The lower curve in Figure 11 shows the concentration of open water / new ice (right scale). There is none to speak of in November and December, then a spike (5%) in mid- to late-January, then a steady 1-2% for the rest of the winter and spring. The spike corresponds to the large divergence event in January (Figure 4) and the dip in multiyear ice concentration (upper curves). To complete the classification of ice types, ice that is brighter than −23 dB but darker than multiyear ice goes into the "first-year ice" category.
5. Conclusions

We have described and analyzed a unique data set consisting of a time series of 195 high-resolution RADARSAT SAR images centered on the SHEBA station, plus the associated ice motion data on a 5-km grid computed by RGPS, spanning the period from November 1, 1997 to October 8, 1998.

Analysis of the ice deformation shows a clear distinction between winter and summer conditions. Winter is characterized by linear intersecting zones of high deformation (active cracks) separating plates of rigid ice. Summer is characterized by a more random pattern of deformation due to free drift and low ice strength. The transition from winter to summer conditions occurred abruptly at the end of July in response to a strong storm, after the ice had been melting and weakening for two months. The transition back to winter conditions occurred more gradually from mid-September to early October, as the ice slowly consolidated with dropping temperature.

The time series of radar backscatter also shows seasonal transitions. The backscatter is stable in the fall and early winter (November-December, 1997) with 90% or higher multiyear ice concentration. The backscatter drops slightly in January due to the opening of large leads, and is then very stable throughout the rest of the winter and spring. The onset of melt (May 29) brings a large drop in the mean backscatter, as water in the surface layer obliterates the distinction between ice types in the SAR imagery. The summer signature is strongly affected by the presence of water on the surface, and so fluctuates with the cycles of freezing and thawing. The backscatter jumps abruptly on August 14-15, signaling the start of fall freeze-up. Multiyear ice, first-year ice, and open water / new ice can be distinguished in fall/winter/spring but not during the summer melt season.

Future work with the data sets described here will focus on tying together the kinematics and the radiometry more closely. In addition, the RGPS at the Alaska SAR Facility is currently turning out data products for the SHEBA year that consist of ice deformation and thickness (the thin end of the distribution) for the entire western Arctic. This should prove to be a rich data set for SHEBA investigators.

Acknowledgements

We thank the Alaska SAR Facility in Fairbanks for providing the RADARSAT SAR imagery and the calibration software. We thank Ron Kwok and the RGPS team at JPL for creating the special ice motion data set for SHEBA. The meteorological data are courtesy of the SHEBA Project Office. This work was performed under grant OPP9720144 from the National Science Foundation in support of the SHEBA Project Office at the University of Washington.

References


**Figure Captions**

**Figure 1.** RADARSAT SAR image frames of January 10 and 11, 1998, illustrating the overlap that allows features in the first image to be tracked in the second image. The SHEBA drift track is also shown, with the position on January 11 marked by a small dot. Centered on the dot are two squares, 40 x 40 km and 200 x 200 km, showing the extent of the sub-images that have been extracted from the original SAR image.

**Figure 2.** RADARSAT SAR image of January 11, 1998. The SHEBA station is at the center of the yellow box, which measures 40 x 40 km. The grid illustrates the relative motion of the sea ice since the previous day. Red cells have remained rigid; green cells have deformed more than 15% (|ε| > 0.15). (Image copyright CSA 1998).

**Figure 3.** RADARSAT SAR sub-image of the 40 x 40 km region centered on the SHEBA station on January 11, 1998. This is a close-up of the yellow box in Figure 2. (Image copyright CSA 1998).

**Figure 4.** Time series of ice divergence in the vicinity of the SHEBA station, computed at four different spatial scales (averaging sizes) centered on the station.
Figure 5. The spatial pattern of the magnitude of the ice strain, $|\varepsilon|$, over 12 time intervals in the summer of 1998. Each panel is 200 x 200 km in size, with the SHEBA station at the center. Each 5-km cell is color-coded according to $|\varepsilon|$ for that cell, from blue ($|\varepsilon| = 0$) through the spectrum to red ($|\varepsilon| > 0.25$). Day 196 is July 15 and Day 214 is August 2.

Figure 6. Standard deviation of backscatter vs. mean backscatter. Each symbol represents one 40 x 40 km sub-image. The slope of the linear relationship changes with season.

Figure 7. Mean backscatter vs. incidence angle. Each symbol represents one 40 x 40 km sub-image. The drop in backscatter from fall to winter/spring is due to the changing mix of ice types within the 40-km image frames.

Figure 8. Mean backscatter vs. time for the 40 x 40 km sub-images. The high frequency variations are due to different incidence angles. The heavy line is an adjustment of the mean backscatter to a standard incidence angle of 32.5°. The mean winter backscatter is very stable compared to other seasons. Melt onset and freeze-up are marked by vertical dotted lines at May 29 (day 149) and August 15 (day 227).

Figure 9. Daily 2-meter air temperature interpolated to the SAR image times (upper curve, left scale) and mean backscatter (adjusted to 32.5° incidence angle, lower curve, right scale) vs. time from May 25 (day 145) to September 7 (day 250). Melt onset and freeze-up are marked by vertical dotted lines at May 29 (day 149) and August 15 (day 227).

Figure 10. Mean backscatter (adjusted to 32.5° incidence angle) vs. time following a patch of multiyear ice (circles) and lead ice (triangles). The two ice types are generally well separated but lead ice can brighten briefly in the early stages of its formation, as on January 10-11.

Figure 11. Multiyear ice concentration (upper curves, left scale) for three different thresholds, and open water / new ice concentration (lower curve, right scale). The SAR sub-images that follow the SHEBA station are not true Lagrangian elements – ice does advect in and out of the 40-km frames, so the concentration of multiyear ice is not constant.