EVALUATION OF ARCTIC OPERATIONAL PASSIVE MICROWAVE PRODUCTS: A CASE STUDY IN THE BARENTS SEA DURING OCTOBER 2001

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ABSTRACT
Microwave satellite imagery products are an important resource for characterizing the sea ice environment because of their frequent, all-weather coverage of the polar regions. They are, however, limited by spatial resolution, atmospheric effects, and surface ambiguities in the microwave signal. New SSM/I ice concentration algorithms are now available in near real-time for operational forecasting and analysis. The Barents Sea is a region of operational interest, but is characterized by complex ice formation processes and a mixture of several different ice types. In October 2001, the U.S. Coast Guard icebreaker Healy collected information on ice conditions in the region and coincident high resolution Radarsat and DMSP OLS imagery were also obtained. The high-resolution imagery were used evaluate and interpret the microwave imagery. The evaluations indicate that the new SSM/I algorithms yield improved characterization of thin ice near the ice edge, without noticeable weather contamination.

INTRODUCTION
The presence of sea ice in the Arctic significantly affects the regional climate, wildlife, and human activities in the region. As such, there is considerable interest in improving estimates of the extent and quality of the sea ice cover. Because of the remoteness and harsh environment of the region, remote sensing is of particular benefit for observing the Arctic. Many types of sensors can be used to detect sea ice including visible, infrared, active microwave (scatterometers and synthetic aperture radar [SAR]), and passive microwave. Microwave instruments have distinct advantages over the other types of sensors because they can provide long-term complete daily coverage in all sky conditions. However, passive microwave sensors also have several disadvantages that limit their effectiveness, most notably low resolution and ambiguities in the surface signal (especially in summer).

The Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) and preceding passive microwave sensors have provided observations of sea ice extent and concentration since 1972. This long-term record has

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provided valuable climatological information about the Arctic sea ice cover and has indicated a downward trend in summer sea ice extent, a possible result of global warming (Comiso, 2002; Johannessen et al., 1999; Parkinson et al., 1999).

The limitations of SSM/I make it ill suited to operational ice analysis, where precision and accuracy are paramount. However, due to cloud cover and limited coverage by other sensors, it is often the only information available. Thus there is considerable interest in improving SSM/I-derived ice concentrations.

In this study, we follow-up an ongoing general comparison with Advanced Very High Resolution Radiometer (AVHRR) imagery (Meier et al., 2001) by presenting a case-study evaluation of Barents Sea ice concentrations from four different SSM/I algorithms through qualitative comparisons with Radarsat-1 SAR imagery. In particular, we compare established all-sky algorithms with a new algorithm potentially susceptible to cloud contamination under cloudy conditions. The Barents Sea region was chosen because it is of operational interest, it includes a mixture of ice types (frazil, pancake ice to multiyear floes), and the U.S. Coast Guard Cutter Healy was in the region during October 2001 providing on-site observations of the conditions.

**DATA**

Sea ice concentration fields used here were obtained from algorithms run at the U.S. National Ice Center (NIC) in Washington. These products are distributed daily in near real-time at the NIC via the internet (http://www.natice.noaa.gov/science/). The algorithms employ brightness temperature fields obtained from the DMSP via NOAA. The algorithms are run using SSM/I brightness temperature swath data and then are composited into 24-hour daily average fields on the National Snow and Ice Data Center (NSIDC) 25 km resolution polar stereographic projection (Maslanik and Stroeve, 2002).

Radarsat imagery was acquired at the NIC from the Canadian Space Agency. The initial 100 m resolution was subsampled to 500 m and mapped to the NSIDC grid to be consistent with the SSM/I concentrations. DMSP Optical Linescan System (OLS) visible and infrared imagery, used in evaluation of the sky conditions, were also obtained at the NIC. AVHRR imagery was obtained at the Danish Meteorological Institute in Copenhagen, Denmark.

**SSM/I ALGORITHMS**

Sea ice concentrations can be derived from combinations of two or more of the seven SSM/I brightness temperature channels (19 GHz, 37 GHz, 22 GHz and 85 GHz, all except 22 GHz dual, horizontally and vertically, polarized). Several algorithms have been developed and four algorithms were selected for this study: the NASA Team (NT), the Bootstrap (BS), the Cal/Val (CV), and the enhanced NASA Team or NASA Team 2 (N2). The NT and BS algorithms were selected because they have been the most widely used historically. The CV algorithm was developed from the calibration and validation of the SSM/I sensor and was the operational algorithm used by the NIC. The N2 is the most recently developed algorithm and is currently used operationally by the NIC. All algorithm products were created on the NSIDC 25-km polar stereographic grid. For brevity, the algorithms will not be discussed in detail here. For more information on the algorithms, see the references cited for each below or Meier et al. (2001).
**NASA Team**
The NASA Team algorithm uses polarization and gradient (frequency) ratios of the 19V, 19H, and 37V GHz channels (Cavalieri et al., 1984; Comiso et al., 1997). The use of ratios removes the effect of the physical surface temperature. A weather filter is employed to eliminate erroneous ice retrievals over wind-roughened or cloud-covered ocean (Gloersen and Cavalieri, 1986). This weather filter is also used in the other three algorithms. Hemispheric tie points are used for 100% ice and 100% water.

**Bootstrap**
The Bootstrap uses a linear combination of the 19V, 19H, and 37V channels to interpolate between 100% ice and 100% water tie points (Comiso et al., 1997). Tie points are adjusted seasonally, with two sets of summer tie points, to account for changing emissive properties during the melt and freeze seasons.

**Cal/Val**
The Cal/Val algorithm (Hollinger et al., 1991) is a modified version of the AES-York algorithm (Ramseier et al., 1988). In the interior of the pack, a linear combination of the 19V and 37V channels is used to obtain ice concentration. Near the ice edge, 37H and 37V are used. This potentially yields a more precise ice edge because the footprint of the 37 GHz channels (38 × 30 km) is smaller than the 19 GHz channels (70 × 45 km), although all channels are gridded to the same 25 km resolution.

**NASA Team 2**
The NASA Team 2 is an enhanced version of the original NT and is formulated similarly (Markus and Cavalieri, 2000). The N2 algorithm is unique from the other three algorithms because it employs the 85 GHz channels. Historically, the 85 GHz channels have been avoided for sea ice retrievals because the atmosphere often substantially contributes to the emission signal at 85 GHz; liquid water in clouds can be a particularly strong emitter at 85 GHz. The N2 corrects for the atmospheric contribution through the use of a simple forward radiative transfer model. The radiative transfer model is run for 11 typical polar atmospheric conditions. The closest match to the raw 85 GHz brightness temperatures is selected to then correct the raw values and provide “clear sky” 85 GHz temperatures.

The 85 GHz channel is an additional frequency compared to the other algorithms, which use only 19 and 37 GHz, and thus can provide complementary information for estimating ice concentration. In addition, the 85 GHz channels are less sensitive to the effects of surface inhomogeneities (e.g., snow moisture content) and thus they also potentially provide enhanced surface information. Because the 85 GHz channels have a smaller pixel size compared to the other channels (12.5 km vs. 25 km), there is also potential for improved spatial resolution; however, this was not taken advantage of here.

**RESULTS**
The algorithms were first evaluated during summer (June – August 2001) and winter (December 2001 – March 2002) clear-sky conditions through comparisons with AVHRR imagery. In summer, ice concentrations are calculated from near-infrared AVHRR channel 2 (0.7–1.1 µm) imagery using a mixing method (linear interpolation between 100% ice and 100% water tie points; tie points were chosen locally within each image to reduce errors from surface variations, such as meltponds). Winter ice
concentrations are calculated from thermal infrared AHVRR channel 4 (10.3–11.3 µm) imagery using a threshold temperature (~271 K) to discriminate ice from water. This approach is based on methods employed in previous SSM/I-AVHRR ice concentration comparisons (e.g., Comiso and Steffen, 2001; Emery et al., 1991)

**General Results**
There are substantial differences in the performance of the algorithms during the winter (Table 1) and summer (Table 2) seasons. In winter, the CV algorithm has the lowest bias and RMS error. The other three algorithms have similar RMS errors as CV, but they underestimate ice concentration much more than CV. Of the three, N2’s bias is about 40% smaller than BS or NT.

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<th>BS</th>
<th>CV</th>
<th>N2</th>
<th>NT</th>
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<tbody>
<tr>
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<td>RMS</td>
<td>10.2</td>
<td>9.5</td>
<td>9.8</td>
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Table 1: Winter SSM/I-AVHRR percent sea ice concentration difference. 3435 samples total.

The very low CV bias is primarily due to the character of the CV algorithm. It is formulated to be very sensitive to the presence of any ice. As ice concentrations increase, the CV algorithm quickly saturates and returns concentrations much higher than 100%. These non-physical values are truncated to 100% in the concentration product. In the winter, the Arctic is nearly totally ice-covered over most of the region. Thus a consistent 100% estimate is quite accurate.

The situation is quite different in summer. Here, the saturation of CV yields a large overestimation of ice concentration. The BS algorithm slightly underestimates concentration and the N2 algorithm slightly overestimates concentration. The use of varying tie points during the summer is probably responsible for the BS algorithm’s improved accuracy. The added information from the 85 GHz channel improves the N2 algorithm’s accuracy. The NT algorithm considerably underestimates concentration; this is consistent with many previous evaluations of NT (e.g., Comiso et al., 1997). The RMS errors for all algorithms during summer are higher than winter due to the greater variability in the summer sea ice surface from melting snow, melt ponds, and leads.

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<th>BS</th>
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<th>NT</th>
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<tbody>
<tr>
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<td>1.1</td>
<td>-9.0</td>
</tr>
<tr>
<td>RMS</td>
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<td>19.6</td>
<td>19.8</td>
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Table 2: Summer SSM/I-AVHRR percent sea ice concentration difference. 8868 samples total.

While the CV algorithm has the lowest error in winter and the BS algorithm has the lowest error in summer, the N2 algorithm is consistently among the best one or two algorithms in both the summer and winter. This suggests that the N2 algorithm may be a good, robust all-season algorithm. However, these general conclusions are based on clear-sky comparisons only. Because the N2 relies on the 85 GHz channel, the errors could be higher under cloudy conditions if the simple radiative transfer correction does not fully account for the atmospheric effects.
Barents Sea October 2002 Case Study

During October 2002, the USCGC Healy conducted a field study in the Barents Sea region. In conjunction with this study, the NIC collected a dense set of OLS visible and infrared imagery and Radarsat-1 SAR imagery from a region near Svalbard (Figure 1). Nineteen Radarsat images collected between 1 October and 19 October provided the opportunity to evaluate the SSM/I ice concentration algorithms, particularly the NASA Team 2 algorithm under cloud-covered conditions. According to observations from the Healy, conditions were mostly cloudy in the region. OLS imagery was used to select days where Radarsat-covered areas were particularly cloudy.

Figure 1: Map of Arctic with Radarsat region outlined by box near Svalbard.

Because of the complexity of the Radarsat imagery and the large difference in resolution between Radarsat and SSM/I, direct quantitative comparison is difficult. Here, we select Radarsat imagery (in cloud-covered areas) that includes the ice edge and overlay concentration contours from the SSM/I algorithms on the Radarsat image. For brevity, only two cases over three days are discussed here. These two cases are representative of the other cases studied.

1 October
By the beginning of October, ice growth had just started in the region. Thus the ice in the region is primarily late first-year or multiyear floes, with small amounts of new ice. The Radarsat imagery shows a diffuse ice edge due to advection of floes southward (Figure 2). The CV algorithm clearly misses a considerable amount of ice near the edge that the other three algorithms detect. The BS and NT 15 % contour matches up most closely with the edge, in agreement with other studies. For N2, the 5 % contour appears to be most consistent with the ice edge. Thus, despite a theoretically more precise ice edge from CV (due to the smaller footprint of 37 GHz), this case demonstrates that this is not necessarily the case.

One possible explanation for this is that the SSM/I concentrations are based on 24-hour composites. Particularly when ice conditions are changing quickly, the average daily
concentration field may not be representatives of the conditions at a specific time (i.e., the time of the Radarsat image).

Within the ice edge, note that neither the BS algorithm nor the NT algorithm indicate concentrations above 90% (there is no 90% contour in either image). However, from the Radarsat imagery it is evident that over much of the ice-covered area the concentration is near 100%. Both the CV and N2 algorithm concentrations more closely represent the ice conditions in the region. While the ice edge is of primary importance operationally, conditions within the ice are also of concern. A ship may be able to navigate through a region of 50% ice cover, but could encounter severe difficulties in a compact ice region of near 100% concentration.

Figure 2: Radarsat image from 1 October overlaid with SSM/I concentration contours. From the ice edge into the ice, contour levels are: 5%, 15%, 50%, 90%. The brighter region on the left side of the image is wind roughened open water. North is to the bottom right. © Canadian Space Agency (2001).

11-12 October
After the first week of October, freeze-up has begun. This is evident in the high-contrast return in the lower left corner of the images in Figure 3 indicating a frazil or grease ice slick. The BS algorithm detects this, as does the N2 (and NT) algorithm to
some extent. However, the CV algorithm misses nearly all of the new ice.

Again, conditions can change considerably over the course of the 24-hour composites and the SSM/I concentrations may not be representative of the time of the Radarsat scene. However, in the situation here, ice growth is occurring (as opposed to the ice advection on 1 October). The CV algorithm is sensitive to the presence of any ice and would be expected to detect the frazil growth. Since the BS and N2 algorithms clearly indicate the new ice growth, it can be concluded than in at least some cases, the BS and N2 algorithms are more adept at detecting new ice than the CV algorithm. This is further indicated in the Radarsat image of the following day (Figure 4), where the new ice has grown in place, but the CV algorithm still does not detect the ice.

Another feature of note is the region of lower concentration in the upper right of the 11 October Radarsat image. This is an area of large floes that are less compact than the surrounding ice. The N2 algorithm’s 90 % contour coincides quite closely with this region. The other three algorithms do not detect this feature. While the concentration is
likely close to 90 % in the less compact region, this demonstrates the ability of the N2 algorithm to obtain enhanced surface information through the use of the 85 GHz channel and pick up details missed by the other algorithms.

Figure 4: Radarsat image from 12 October overlaid with SSM/I concentration contours. From the ice edge into the ice, contour levels are: 5 %, 15 %, 50 %, 90 %. North is to the bottom right. © Canadian Space Agency (2001).

CONCLUSIONS
From the two case studies presented here, the BS and N2 algorithms generally provide the best qualitative agreement with the Radarsat imagery. Somewhat surprisingly, the CV tends to underestimate the ice edge (misses ice), although some of this may be explained by advection. While the ice edge from the NT algorithm compares reasonably well with the BS and N2, the NT algorithm appears to grossly underestimate overall ice concentration, in agreement with many other studies (e.g., Comiso et al., 1997).

These results indicate that the N2 algorithm performs as well or better than the other three algorithms in characterizing conditions near the ice edge. These two cases are both in cloudy skies, particularly on the 11th and 12th when thick clouds covered the entire region as a front moved through the area. Thus, the simple forward radiative
transfer model of the N2 algorithm appears to be able to correctly account for the atmospheric influence and yield accurate ice concentrations in all-sky conditions.

Errors in the algorithms can result from many sources. Surface inhomogeneities (snow cover, etc.) is a major source of error. Use of hemispheric tie points can result in significant errors in regions where the tie points are not representative of the ice cover; this is particularly true in regions of new and young ice (Steffen et al., 1992). Atmospheric effects (clouds, precipitation) can cause errors. The use of daily-averaged concentration fields, especially in comparison with Radarsat snapshot images, results in disagreements between the two fields. Finally, a major limitation of SSM/I-derived ice concentrations is the spatial resolution (25 km gridded resolution, with a lower instantaneous field-of-view depending on the frequencies employed).

The two cases presented here are representative of comparisons (omitted here for brevity) with several other Radarsat images acquired in the Barents Sea during October 2002. Although N2 concentrations have been shown to be accurate in summer and winter under clear skies, there could be seasonal variability in the N2 algorithm’s performance in cloud-covered conditions. Further case studies under cloudy skies at other times of the year are necessary to fully verify the utility of the N2 algorithm. Additionally, there could be regional variation in the effectiveness of the algorithms. Finally, there may be benefits from using meteorological data to correct 85 GHz brightness temperatures instead of the simple model used in the N2 algorithm (Kern and Kaleschke, 2002), although this may not be practical for operational products. Operational ice concentrations from the Advanced Microwave Scanning Radiometer (AMSR) are now available. With its improved spatial resolution (as low as 5 km) and other improvements, AMSR may provide much improved sea ice information over SSM/I.

ACKNOWLEDGEMENT
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