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Impact of Surface Roughness on AMSR-E Sea Ice Products

Julienne C. Stroeve, Thorsten Markus, *Member, IEEE*, James A. Maslanik, Donald J. Cavalieri, *Member, IEEE*,
Albin J. Gasiewski, *Fellow, IEEE*, John F. Heinrichs, *Member, IEEE*, Jon Holmgren,
Donald K. Perovich, and Matthew Sturm

***Abstract*—This paper examines the sensitivity of Advanced Microwave Scanning Radiometer (AMSR-E) brightness temperatures (Tbs) to surface roughness by a using radiative transfer model to simulate AMSR-E Tbs as a function of incidence angle at which the surface is viewed. The simulated Tbs are then used to examine the influence that surface roughness has on two operational sea ice algorithms, namely: 1) the National Aeronautics and Space Administration Team (NT) algorithm and 2) the enhanced NT algorithm, as well as the impact of roughness on the AMSR-E snow depth algorithm. Surface snow and ice data collected during the AMSR-Ice03 field campaign held in March 2003 near Barrow, AK, were used to force the radiative transfer model, and resultant modeled Tbs are compared with airborne passive microwave observations from the Polarimetric Scanning Radiometer. Results indicate that passive microwave Tbs are very sensitive even to small variations in incidence angle, which can cause either an over- or underestimation of the true amount of sea ice in the pixel area viewed. For example, this paper showed that if the sea ice areas modeled in this paper were assumed to be completely smooth, sea ice concentrations were underestimated by nearly 14% using the NT sea ice algorithm and by 7% using the enhanced NT algorithm. A comparison of polarization ratios (PRs) at 10.7, 18.7, and 37 GHz indicates that each channel responds to different degrees of surface roughness and suggests that the PR at 10.7 GHz can be useful for identifying locations of heavily ridged or rubbled ice. Using the PR at 10.7 GHz to derive an "effective" viewing angle, which is used as a proxy for surface roughness, resulted in more accurate retrievals of sea ice concentration for both algorithms. The AMSR-E snow depth algorithm was found to be extremely sensitive to instrument calibration and sensor viewing angle, and it is concluded that more work is needed to investigate the sensitivity of the gradient ratio at 37 and 18.7 GHz to these factors to improve snow depth retrievals from spaceborne passive microwave sensors.**

***Index Terms*—Passive microwave, remote sensing, sea ice.**

I. INTRODUCTION

OBSERVATIONS from successive multichannel passive microwave satellite sensors provide nearly 30 years of sea ice observations for the Arctic and Antarctic. Data from passive microwave radiometers first became available in December 1972 from the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR). However, it was not until 1978, with the launch of the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), that the polar regions became routinely observed using multichannel passive microwave sensors. SMMR was followed by a series of successive Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) sensors in 1987. The Advanced Microwave Scanning Radiometer (AMSR-E) continues this relatively long history of polar remote sensing.

Several algorithms have been developed to estimate the fraction of sea ice in the polar oceans from satellite passive microwave observations (e.g., [3], [4], [10], and [13]). Analysis of sea ice extent using the National Aeronautics and Space Administration (NASA) Team (NT) sea ice algorithm [2], [3] has shown that Arctic sea ice has rapidly declined since the late 1970s [16]. However, to make these types of assessments, consistent data sets from similar sensors on successive spacecraft are needed. This requires understanding differences in ice concentration estimates from similar sensors as well as understanding differences resulting from changes in sea ice algorithms. In an earlier paper, differences in ice concentrations and ice extent between successive SSM/I instruments were documented [17]. Although the sea ice algorithm was consistent between the sensors, this paper showed that significant regional differences in ice concentrations and ice extent exist between the different SSM/Is (e.g., F8, F11, and F13) and revealed that earlier efforts to match orbital antenna temperatures or gridded brightness temperatures (Tbs) between different sensors were insufficient to remove regional biases in Tbs and subsequently in the derived sea ice concentrations. The approach taken by Cavalieri *et al.* [2] is to tune the algorithm tie points (reference Tbs) for each sensor to minimize differences in ice extent during sensor overlap periods. However, despite this approach, regional biases in ice concentration remain.

Improved polar ocean products are expected from AMSR-E because of additional spectral channels, greater spatial resolution, and enhanced system performance. The AMSR-E sea ice algorithm uses a revised version of the NT algorithm, which is referred here as the NT2 algorithm, to retrieve the total fraction of sea ice per pixel [10]. In addition, snow depth over seasonal ice is retrieved using the snow depth algorithm of Markus and

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J. C. Stroeve is with the National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309 USA (e-mail: stroeve@kodiak.colorado.edu).

T. Markus and D. J. Cavalieri are with the National Aeronautics and Space Administration-Goddard Space Flight Center, Greenbelt, MD 20771 USA.

J. A. Maslanik is with the Colorado Center for Astrodynamics Research, University of Colorado at Boulder, Boulder, CO 80309 USA.

A. J. Gasiewski is with the Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO 80309 USA.

J. F. Heinrichs is with the Department of Geosciences, Fort Hays State University, Hays, KS 67601 USA.

J. Holmgren and M. Sturm are with the U.S. Army Cold Regions Research and Engineering Laboratory-Alaska, Fort Wainwright, AK 99703 USA.

D. K. Perovich is with the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755 USA.

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Cavalieri [11] applied to the AMSR-E Tbs. Using AMSR-E to extend the sea ice extent/concentration time series provided by SMMR and SSM/I will require quantifying the differences in ice concentration induced not only by the use of a different sensor but also by the use of a different sea ice algorithm. We can expect considerable and essentially unexplained differences to exist in ice concentrations produced by the NT2 and NT algorithms. Ice concentration variations may result from the use of different sets of channels in the algorithms; different responses to changes in atmospheric conditions, surface temperatures, and emissivities; different algorithm tie points; and differences in the ways that the tie points are selected [13]. Radiative transfer modeling (RTM) sensitivity experiments (not shown) suggest that differences may also result from the ways in which the algorithms respond to variations in snowpack conditions such as depth hoar, snow depth/density, ice lenses, and flooding at the snow/ice interface.

Whereas the NT2 algorithm incorporates an RTM component (as part of the atmospheric correction step), the standard validation plan does not use RTM as a validation tool. Such modeling is an integral part of a number of other AMSR product validation efforts. The use of an RTM approach that combines sea ice and atmospheric components to simulate radiances at AMSR-E frequencies allows for the opportunity to extend subjective comparisons between algorithms and sensors and assess the degree to which observed differences can be attributed to surface and/or atmospheric conditions.

Therefore, to improve our understanding of differences in ice concentrations resulting from changes in sea ice algorithms as well as changes in sensors, a modeling approach is used. Two different types of models were used for this effort, namely: 1) the Microwave Emission Model of Layered Snowpacks (MEMLS) [21] and 2) the MicroWave MODel (MWMOD) [6]. MEMLS is a thermal microwave emission model and is based on radiative transfer, taking multiple-volume scattering and absorption into account. Since microwave scattering efficiency depends upon snowpack properties, the model accounts for parameters such as grain size, density, temperature, and liquid water content. MWMOD is an emission model developed for use with a layered sea ice column and snow cover and includes an atmospheric model. Powell *et al.* [12] discuss the MEMLS model in more detail and investigates the response of snow physical properties and snow layering on AMSR-E Tbs using MEMLS. Two unanswered questions remain, however. One is the effect of the emissivity of the underlying sea ice, and the other is the impact of surface roughness. In this paper, we investigate how observed variations in Tbs obtained during a field campaign in March 2003 near Barrow, AK, can be explained by variations in surface roughness using model calculations from MWMOD. This effort will help to assess the role that roughness plays in ice concentration and snow depth retrieval algorithms.

IV. CONCLUSION

This paper uses an RTM approach to simulate Tbs over sea ice near Barrow, AK, obtained from PSR aircraft observations and investigates the impact of Tbs and subsequently derived sea ice concentrations and snow depth on surface roughness. For this analysis, a combined ocean/sea ice/atmospheric model (MWMOD) is used to simulate AMSR-E Tbs over Elson Lagoon and the Beaufort Sea. The first analysis focused on determining the ability of MWMOD to simulate the observed Tbs. Results showed that, in general, MWMOD is able to accurately simulate Tbs over the FYI examined in this paper. Results are better at horizontal polarizations than at vertical ones, but given the uncertainties in the calibration of the PSR Tbs, it remains unclear if the differences between observed and modeled Tbs are a result of the inability of the model to accurately simulate the vertical polarizations, especially at lower frequencies. At 37 GHz, MWMOD output matches observations to within about 1 K. We were not able to evaluate the sensitivity of the 89-GHz channel to sea ice properties because of calibration issues. This was unfortunate, since the 89-GHz channel plays a central role in the AMSR-E sea ice algorithm (e.g., NT2).

Comparisons between modeled PRs at 10.7 GHz with those from the PSR confirm that the PR decreases as the surface becomes more ridged/rubbled. It is apparent that passive microwave Tbs are very sensitive to the orientation of the surface elements relative to the sensor viewing angle, which, in turn, can result in different retrievals of ice concentration and snow depth from sea ice algorithms. In this paper, the roughness facets appear to be oriented toward the PSR and therefore yield emissions at angles less than 55°. For example, at the Beaufort Sea stake locations, we found a reduction in the "effective" incidence angle over the Beaufort Sea compared with Elson Lagoon. The smoother surface of Elson Lagoon exhibited gradual slopes on the order of 5°–10°, whereas the rougher Beaufort Sea showed slopes on the order of 13°–20°. ATM rms height estimates as well as standard deviation of ice thickness around the stake locations confirm the relationship between the PR at 10.7 and the changes in the effective incidence angle and the roughness of the surface. A relationship is also observed at 18.7 GHz, but not as strong as at 10.7 GHz, which suggests that the PR at 10.7 GHz can provide good estimates of areas of ridged and heavily rubbled ice. At 37 GHz, snow masks the underlying ice roughness, and therefore, PR37 is not a useful measure of surface roughness as indicated by the decrease in correlation between roughness and PR37 in Table III. Results here are in agreement with the results presented in [9].

The orientation of the roughness facets relative to the sensor strongly influences the Tbs and therefore the sea ice concentration returned by the NT2 and NT sea ice algorithms. The dependence of algorithm performance on incidence angle is less for the NT2 algorithm than for the NT algorithm, but both algorithms can significantly underestimate the fraction of sea ice if the effective incidence angle is unknown. If we assume a flat surface and a constant PSR incidence angle of 55°, the amount of sea ice can be underestimated by more than 20% for the sea ice areas sampled in this paper. Using the effective incidence angle derived through comparisons of PR10.7 results in ice concentrations typically within a couple percent of those observed, except at stake location 5.20 km.

Results here also confirm that the Tbs are sensitive to small variations in incidence angles near 50° such as those induced by changing from the SMMR to SSM/I, and AMSR instruments could induce differences in ice concentration estimates on the order of 5%–10%. This is not a factor typically considered when combining sea ice concentration data sets that span several satellite sensors, and depending on the amount of open water present, the differences could be greater. However, it is important to keep in mind that over the larger satellite footprint, these features may be "smoothed" out. This needs to be investigated in more detail.