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Assessment of the AMSR-E Sea Ice Concentration Product at the Ice Edge Using RADARSAT-1 and MODIS Imagery

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***Abstract*—Imagery from the C-band synthetic aperture radar (SAR) aboard RADARSAT-1 and the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to evaluate the performance of the Advanced Microwave Scanning Radiometer–EOS (AMSR-E) ice concentration product near the sea ice edge in the Bering Sea for four days during March 2003, which is concurrent with the AMSR-Ice03 field/aircraft campaign. The AMSR-E products were observed to perform very well in identifying open-water and pack-ice areas, although the AMSR-E products occasionally underestimate ice concentration in areas with thin ice. The position of the ice edge determined from AMSR-E data using a 15% concentration threshold was found to be, on average, within one AMSR-E grid square (12.5 km) of the ice edge determined from the SAR data, with the AMSR-E edge tending to be outside the SAR-derived edge.**

***Index Terms*—Passive microwave remote sensing, sea ice edge, synthetic aperture radar (SAR), validation.**

I. INTRODUCTION

THE AREA near the sea ice edge, which is known as the marginal ice zone (MIZ), is of considerable significance for scientific study and operational sea ice monitoring. The location of the ice edge is important for estimating the total sea ice extent, a critical parameter for determining the overall mass balance of sea ice cover. Sea ice is both a driver and indicator of climate change due to the sea ice albedo feedback [1] and the sensitivity of sea ice to temperature increases in the polar regions [2]. Recent research shows that the Arctic sea ice extent has decreased since 1978 [3], and evidence suggests that the Arctic may become seasonally ice free [4]. During Arctic spring, upwelling along the ice edge triggers a bloom of plankton, which is vital as the base for the Arctic marine ecosystem [5]. Polar lows often form from the baroclinic instability associated with the pack ice edge [6]. Finally, sea ice represents a significant shipping hazard [7], and for this reason, many nations maintain operational sea ice monitoring agencies to identify the position of the ice edge.

Ships and aircraft can be used to map the sea ice edge, but the resource and time requirements for this approach over large areas are prohibitive. Remote sensing using spaceborne instruments has therefore become widespread among the operational and research sea ice communities. Because sea ice generally has higher albedo than ice-free ocean [8], visible wavelength imagery from satellites can be useful for studying the sea ice edge and the nearby MIZ. Thermal infrared satellite imagery can also be used to map ice in the MIZ since sea ice has low thermal conductivity and usually appears colder than adjacent ocean areas [8]. However, sensors operating in the visible and thermal infrared portions of the electromagnetic spectrum are severely affected by clouds and fog, which obscure the ice edge about 70% of the time [9]. Furthermore, visible imagery cannot be used during the polar night. An alternative choice is the use of passive sensors (radiometers) operating in the microwave portion of the spectrum. These instruments are effective for observing sea ice, are not affected by polar darkness, and are able to observe an ice surface through cloud cover.

The response of passive microwave sensors to a sea ice cover is more complex than that of visible or infrared sensors. At microwave wavelengths, an ice-free ocean surface is reflective and has low emissivity; thus it appears radiometrically cold [10]. In addition, the emission from the ocean surface is highly polarized, with the emissivity at vertical polarization being greater than that at horizontal polarization. Once sea ice grows to a thickness of approximately 10 cm, its radiometric properties change considerably, the emissivity of the ice increases, and the polarization of the emitted radiation decreases [10]. These changes continue as the ice thickens, and the radiometric characteristics of the ice are further altered during the melt season, when liquid meltwater appears in the snow cover and collects in melt ponds. If sea ice survives a melt season, brine pockets below the ice surface are drained, leaving a layer of bubbles that act as scatterers and decrease the emissivity of the ice [10].

In addition to their response to sea ice characteristics, passive microwave radiometers can provide near-complete daily coverage of the polar regions—an important advantage for monitoring sea ice processes at synoptic scales. A series of passive microwave sensors has been used to measure sea ice characteristics, including the position of the ice edge, beginning with the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR) in 1973 [11] and continuing with the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) in 1978 [12] and the Special Sensor Microwave/Imager (SSM/I) in 1987 [13]. A new generation of passive microwave sensors is represented by the Advanced Microwave Scanning Radiometer–EOS (AMSR-E). The AMSR-E was developed by the Japanese Exploration Agency (JAXA) and has been operating aboard National Aeronautics and Space Administration's

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TABLE I
Channel Center Frequencies and Instantaneous Fields of View for Equivalent Channels of SSM/I [13] and AMSR-E [14]. Note That SSM/I Does Not Have Equivalents for the 6.925- and 10.65-GHz Channels Aboard AMSR-E

SSM/I		AMSR-E	
Center Frequency (GHz)	IFOV (km) – Along Track x Cross-Track	Center Frequency (GHz)	IFOV (km) – Along Track x Cross-Track
----	----	6.925	75x43
----	----	10.65	51x29
19.35	69x43	18.7	27x16
22.235	60x40	23.8	32x18
37.0	37x28	36.5	14x8.2
85.5	15x13	89.0	6.5x3.7 (A) 5.9x3.5 (B)

(NASA) Aqua platform since May 2002 [14]. One of the main improvements of AMSR-E over previous passive microwave sensors is substantially higher spatial resolution. Table I shows that the Instantaneous Fields of View for most AMSR-E channels are less than half that for equivalent channels on the SSM/I. Thus, AMSR-E can produce estimates of sea ice geophysical parameters at much higher spatial resolution than earlier sensors.

The primary way data from passive microwave sensors are used to map sea ice cover is by estimating the sea ice concentration, which is defined as the percentage of an ocean area covered by sea ice. Several algorithms have been developed to estimate sea ice concentration from passive microwave instruments, and all of them exploit the emissivity characteristics previously described [15], [16]. One of these algorithms, the NASA Team Algorithm (NT) deserves a more detailed description here.

The NT was developed originally for the SMMR instrument [17] and is applied operationally to the SSM/I. When used with SSM/I data, the NT calculates a polarization ratio (the difference between the brightness temperatures of the vertically and horizontally polarized 19-GHz channels divided by their sum) and a gradient ratio (the difference between the brightness temperatures of the 19- and 37-GHz vertically polarized channels divided by their sum). First-year (FY) and multiyear (MY) ice concentrations are then calculated as linear combinations of the polarization and gradient ratios. The coefficients in the linear combinations are obtained by collecting brightness temperatures (called tie points) of completely ice-covered and ice-free pixels. The total ice concentration in any SSM/I pixel is calculated as the total of the FY and MY concentrations [17]. There are some factors that complicate the application of the NT. First, certain atmospheric and surface conditions can cause spurious indications of sea ice over open ocean and near the ice edge. Water vapor, liquid water in clouds, and the roughening of the ocean surface by winds and rain can all cause incorrectly elevated sea ice concentration values, particularly at lower ice concentrations [18]. The simplest approach to reducing these weather effects is to set all ice concentrations that are below some threshold to zero. This was done in the earliest large-scale synoptic studies of sea ice, and a threshold of 15% was chosen when it was found that the areal extent of Antarctic sea ice is least sensitive to errors using that value [11]. Other research has confirmed that a threshold in the range of 10%–15% excludes most weather effects [19]. The contour with 15% ice concentration was found to be spatially sharp [20] and, therefore, a good proxy for the ice edge, and the 15% contour continues to be widely used for this purpose [21], [22]. Another technique to address the weather effects, which is the one employed in the NT, is the use of a weather filter in which ice concentrations are set to zero when one or more gradient ratios exceed a threshold [23], [24]. The second complicating factor in ice concentration retrievals is that the presence of liquid water either as melting snow or melt ponds on sea ice alters the emissivity characteristics of the surface. Wet snow acts like a blackbody at microwave wavelengths, causing overestimates of ice concentration, while melt ponds appear like open water, resulting in an underestimate of ice concentration [24]. Thus, during summer and occasionally near the ice edge, where air temperatures are often near freezing, algorithms such as the NT may be unreliable. Third, the emission characteristics of new ice are close to those of open water, and because of this ice concentration, estimates in thin-ice areas are often too low [15], [26].

One of the two standard ice concentration algorithms for the AMSR-E, the NASA Team Algorithm 2 (NT2), was developed for the SSM/I and offers a number of improvements over the NT [27], [28]. The NT2 retains the essential form of its predecessor, specifically, the calculation of polarization and gradient ratios using the 19- and 37-GHz channels (18 and 36 GHz in the case of the AMSR-E). In order to correct for atmospheric effects, the NT2 makes use of the 85-GHz channels (89 GHz for the AMSR-E), which are more sensitive to liquid cloud water and water vapor, by calculating a polarization ratio for the 85-GHz channels and a gradient ratio involving the 85- and 19-GHz vertical-polarization channels. The developers of the NT2 used a forward radiative transfer model to generate a set of estimates for the gradient and polarization ratios based on 12 different atmospheric conditions, three different ice types (including thin ice, MY ice, and FY ice), and all possible ice concentration values. The ice concentration in an SSM/I or AMSR-E pixel is found by choosing the concentration value that yields the best match between the actual and estimated polarization and gradient ratios [27].

Assessments of the performance of the NT2 have been generally positive. The NT2 that uses SSM/I data was initially evaluated against synthetic aperture radar (SAR) and Advanced High Resolution Radiometer (AVHRR) data and was found to be superior to the NT over both the Arctic and the Antarctic [27]. An evaluation of the NT2 applied to SSM/I data in the MIZ, in this case against SAR-derived ice concentrations, found a correlation of 0.66 and a bias toward higher SAR concentrations (i.e., low passive microwave concentrations) of about 5% [25]. A more recent study [16] compared the NT2 applied to SSM/I data against AVHRR ice concentrations in an area near the sea ice edge over an eight-month period and found that the NT2 performed better than the NT, although the NT2 tends to underestimate ice concentrations like other passive microwave algorithms. The NT2 bias was greater in summer than in winter. The performance of the NT2 applied to AMSR-E data has been evaluated against ice concentration information from Landsat-7, the Moderate Resolution Imaging Spectroradiometer (MODIS), and an aircraft passive microwave sensor [29]. An agreement within the range of 5%–10% was observed, however, with slightly negative bias in areas of high divergence because of the presence of young ice.