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Spaceborne Microwave Remote Sensing of Arctic Sea Ice During Spring*

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This paper outlines the fundamental roles sea ice plays during the spring Arctic climate, and it demonstrates the use of passive microwave remote sensing in measuring climatically important sea ice variables during the spring transitional period. It discusses the theoretical concepts underlying passive microwave remote sensing of sea ice, and it summarizes the historical use of satellite microwave radiometry in the Arctic region. In addition, this paper discusses the derivation of climatically important sea ice variables, including sea ice extent, concentration, multiyear ice fraction, and snow melt onset, with additional comments on the precision and accuracy of the remote sensing estimates. It also discusses interannual trends in sea ice extent and presents interannual trends in snow melt onset dates. Finally, this paper provides a brief discussion on the future directions in passive microwave remote sensing of climatically important sea ice variables during the spring transitional period. **Key Words:** climate, microwave remote sensing, sea ice.

Introduction

Snow covered sea ice plays a critical role in the spring Arctic climate by governing energy absorption across the ocean-atmosphere-

ice interface (OAI). During early spring the albedo of a dry snow covered sea ice surface can be as high as 0.98 (Vowinckel and Orvig 1970), limiting energy absorption. However, during snow melt, energy absorption increases dra-

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matically as albedo decreases. The addition of energy further drives melt, setting up a temperature-albedo feedback mechanism that is thought to account for a considerable amount of projected Arctic warming (e.g., Curry et al. 1995). Modelling scenarios suggest this warming could reduce global ice cover by 17×10^6 km² (IPCC 1998).

It is therefore important to characterize sea ice conditions during the spring transition and understand how variability in sea ice conditions corresponds to variability in climate. Owing to the vast spatial scales, harsh climates, and lack of *in situ* data, remote sensing is often relied upon to provide sea ice information. Visual imagery can determine many important sea ice variables, but it is limited to cloud-free conditions when sunlight is available. Infrared imagery can also detect sea ice variables, but it is restricted by cloud cover and the strong Polar inversion layer. Microwave remote sensing, with diurnal and nearly all-weather capabilities, is an ideal technique for obtaining sea ice information. Furthermore, microwave interaction theory with sea ice is a reasonably well developed science (e.g., Carsey 1992), with a 20-year data record available.

This paper examines spaceborne microwave radiometric observations of sea ice during spring. Specifically, it describes how microwave data are used to determine sea ice extent, ice concentration, and multiyear ice fraction, with a more detailed discussion of the estimation of snow melt onset dates. In addition, it illustrates known sources of error in the remote sensing estimates. The analysis is preceded by a background discussion on microwave interaction theory.

Spaceborne Passive Microwave Remote Sensing

In the microwave wavelength region and for temperatures typical of Earth, the Rayleigh-Jeans approximation to Planck's law of thermal radiative emission is most appropriate. The radiative power, usually expressed as a brightness temperature (T_B), is thus proportional to physical temperature (T_S). However, most real objects emit only a fraction of the energy a perfect emitter at the same temperature would radiate. This fraction defines the emissivity (ϵ), such that T_B is given by equation (1).

$$T_B = \epsilon T_S \quad (1)$$

With respect to a particular frequency and polarization, emissivity variations in the Arctic are primarily due to surface variations. For instance, emissivity at 19 GHz vertical polarization is 0.57 for water, 0.94 for first-year ice, and 0.85 for multiyear ice (Eppler et al. 1992). Further information on microwave interaction theory is available in Ulaby et al. (1982, 1986), while the use of microwave remote sensing of sea ice is further discussed in Carsey (1992).

Spaceborne passive microwave imaging measurements began in 1968 with the Soviet Cosmos 243 (Basharinov et al. 1971). This instrument supported four nadir-looking radiometers operating from 3.5 GHz to 37.0 GHz. Launched in 1972, the first National Aeronautics Space Agency (NASA) spaceborne imaging radiometer was the 19.35 GHz Electronically Scanning Microwave Radiometer (ESMR; Zwally et al. 1983). Six years later, a more robust Scanning Multichannel Microwave Radiometer (SMMR) system was launched on the NASA Nimbus-7 (Gloersen et al. 1984). SMMR operated from October 1978 through August 1987 on alternating days to conserve power, and data were collected at 6.6, 10.7, 18.0, 21.0, and 37.0 GHz. Launched in 1987, the most recent additions to orbital passive microwave imaging systems are carried aboard the United States Defense Meteorological Satellite Program (DMSP) satellites. Known as the Special Sensor Microwave/Imagers (SSM/I), these instruments obtain dual polarization information at 19.4, 37.0, and 85.5 GHz, while vertical polarization data are collected at 22.2 GHz (Hollinger et al. 1987). SSM/I sensors have a swath width of approximately 1,400 km, excluding a 2.4° radius around the north pole, and they continue to provide daily coverage of the Arctic.

Spaceborne Passive Microwave Remote Sensing of Sea Ice During Spring

Some of the important sea ice variables to monitor during spring include sea ice concentration, extent, multiyear ice fraction, and especially snow melt onset date. Sea ice concentration is the percentage of area within a pixel that is ice covered, while sea ice extent is the

area poleward of either the ice-ocean edge or a specified contour of sea ice concentration. Both contribute to surface albedo and control energy transfer across the OAI. Multiyear ice fraction is simply the percentage of total ice that is at least two years old. The snow melt onset date is key as it signals a dramatic shift in the energy balance. Energy absorption increases sharply with melt onset, resulting in melt pond formation and sea ice ablation over much of the Arctic.

Derivation of Sea Ice Extent, Ice Concentration, and Multiyear Ice Fraction

In theory, the large emissivity disparity between open water and sea ice provides a convenient means to estimate sea ice extent and ice concentration using SMMR and SSM/I data. Similarly, emissivity differences between first-year and multiyear sea ice can be exploited to estimate multiyear ice fraction. In reality, brightness temperature variations between several channels are used to differentiate open water and sea ice. For example, the NASA Team Algorithm (Cavalieri et al. 1984) uses ratios of 19 (18 on SMMR) and 37 GHz to differentiate open water, first-year sea ice, and multiyear sea ice. Cavalieri et al. (1984) reported that the algorithm is precise to within 5% to 9% for mapping total ice concentration and 13% to 25% for multiyear ice concentration.

Gloersen and Campbell (1991) applied the NASA Team Algorithm to SMMR data and demonstrated a statistically significant decrease of 2.1% in Arctic sea ice extent from 1978–1987. Johannessen et al. (1995) extended the time series to 1994 with SSM/I data and reported an accelerated reduction in Arctic sea ice extent in the post-SMMR period. Recently, Cavalieri et al. (1997) examined the sea ice record from 1978 through 1996 and noted a 2.9% decrease per decade in Arctic ice extent (with a 0.4% margin of error). Further examples of sea ice products derived from the NASA Team Algorithm are available in Zwally et al. (1983), Parkinson et al. (1987), and Gloersen et al. (1992). Other sea ice concentration and extent algorithms include the AES York, NORSEX, U-Mass, and Bootstrap methods. A good description of each is provided by Steffan et al. (1992).

Uncertainties in sea ice extent, ice concentration, and multiyear ice fraction estimates stem from several sources. Instrument errors,

common to all sea ice algorithms, include radiometer noise and poor calibration. Coarse spatial resolution, which leads to mixed pixels, is also a contributing factor (Cavalieri 1992). Gloersen and Cavalieri (1986) reported certain weather effects over the ocean can cause erroneous results. For instance, significant amounts of liquid water in the atmosphere will increase T_B . However, the microwave response is frequency dependent with 37 GHz channels being more sensitive to clouds than 19 GHz channels. Near surface winds also effect T_B , with horizontal polarizations being twice as sensitive as vertical polarizations (Gloersen and Barath 1977). The most significant error in sea ice extent and concentration mapping is likely due to surface emissivity variations. This is especially true for the spring transitional period, when liquid water appears in the snowpack and T_B increases sharply. At this time, sea ice concentration estimates can be in error by as much as 50% (Steffan et al. 1992).

Derivation of Snow Melt Onset Dates

The onset of melt is characterized by an increase in T_B and a drop in albedo owing to an increase in liquid water content within the snowpack (Chang 1984, Mätzler 1987, Onstott et al. 1987). Although the timing of snow melt on sea ice is primarily a function of the annual radiation cycle, atmospheric sensible heat forcing is responsible for interannual variability in the melt. Therefore, monitoring melt onset variations can be used to infer atmospheric conditions.

Historically, melt onset dates were determined by visually examining time series of first-year and multiyear ice fraction components of the NASA team algorithm (Anderson et al. 1985; Anderson 1987a, 1987b). For first-year ice locations, snow melt onset was determined by the fictitious multiyear ice fraction produced by the NASA Team Algorithm. The fictitious multiyear ice fraction was the result of snow melt on the sea ice surface. For multiyear ice locations, melt onset was determined by a fictitious decline in the multiyear ice fraction as determined by the NASA Team Algorithm. However, this technique has several limitations. For example, locations had to be chosen to exclude ice advection and ice type had to be known before melt. Furthermore, there was no way to automate melt onset determination.

Figure 1: Time series analysis of ice coverage and brightness temperature for a first-year sea ice location in the Laptev Sea (72°N, 135°E) in 1990. The triangle represents the melt onset date as determined by the Anderson (1997) algorithm.

Figure 2: Time series analysis of ice coverage and brightness temperature for a multiyear sea ice location in the Arctic Ocean (83°N, 180°W) in 1990. The triangle represents the melt onset date as determined by the Anderson (1997) algorithm.

Table 1 Comparisons between Active and Passive Microwave Derived Melt Onset Dates

Buoy Number	Lat, Long	First Day Buoy Temperatures Are Over Freezing	First Period Buoy Temperatures Are Over Freezing	Extended Period Buoy Temperatures Are Above Freezing	Active Microwave Melt Onset Date*	Passive Microwave Melt Onset Date
7100	74, 140	May 13	May 22	June 17	June 14	May 22
12800	77, 158	May 22	June 1	June 14	June 15	May 22
12801	79, 135	June 16	June 16	June 16	June 18	June 29
12806	73, 155	May 23	May 31	June 8	May 23	May 22
12807	83, 152	July 6	July 6	July 6	June 19	June 20
12808	74.5, 128	June 18	June 18	June 18	June 17	June 20

*Active dates are adapted from Winebrenner et al. (1994).

An automated threshold algorithm was then developed by Anderson (1997) to identify melt onset for any Arctic location, independent of ice type. The algorithm defined the onset of melt when the difference between the 19 GHz horizontal channel and the 37 GHz horizontal channel was less than 2K. Using the horizontal difference and setting the threshold value was accomplished through multiple case studies.

To illustrate the Anderson (1997) snow melt onset algorithm, two time-series plots of T_B are shown, one for a first-year ice location in the Laptev Sea (Fig. 1) and another for a multiyear ice location in the central Arctic Ocean (Fig. 2). In both cases, rapid T_B increases are followed by a decrease in T_B , likely due to snow grain metamorphism. The onset of melt is defined as occurring after Julian day 122 for the first-year location (Fig. 1) and after Julian day 140 for the multiyear location (Fig. 2).

Using active microwave data, Winebrenner et al. (1994) have also developed a melt onset algorithm which assigns a melt date after a

threshold is exceeded. Winebrenner et al. (1994) also compared the active microwave data to buoy and satellite derived surface temperatures. For the majority of the occasions that the active microwave algorithm was triggered by the melt onset, temperatures were near to or above freezing and remained above freezing. When the Anderson (1997) algorithm is applied to passive microwave data for the same locations and compared to the active microwave data similar results are found (Table 1).

To illustrate in more detail the use of passive microwave data for climate studies, melt onset dates have been determined from 1988–1992 using the Anderson (1997) algorithm to show interannual variations (Table 2). The locations used were the same as in Anderson (1987a) and are shown in Figure 3. Results show that some locations have large differences in the melt onset date between years. For example, the first-year ice location in the Laptev Sea (used in Fig. 1) has a 48-day difference between the earliest

Table 2 Melt Onset Dates for Various Locations Around the Arctic

Point	Location	Melt Onset Date					Mean	SD
		1988	1989	1990	1991	1992		
1	Laptev Sea (FYI)	171	134	123	129	141	140	19
2	East Siberian Sea (FYI)	165	99	92*	91*	157	121	37
3	Chukchi Sea (FYI)	161	141	101	142	143	138	25
4	Chukchi Sea (FYI)	120	96	115	111	94	107	10
5	Laptev Sea (MYI)	176	169	149	147	125	153	14
6	Barents Sea (FYI)	135	104	103	98	126	113	17
7	Arctic Ocean (MYI)	163	174	138	158	172	161	15
8	Arctic Ocean (MYI)	163	174	138	185	172	166	20
9	Arctic Ocean (MYI)	182	173	157	186	172	174	13
10	Baffin Bay (FYI)	157	108	115	122	113	123	22
11	Hudson Bay (FYI)	123	104	93	97*	92*	102	13
12	Hudson Bay (FYI)	123	117	92*	111	128	114	13
13	Hudson Bay (FYI)	100	134	93*	111	99	107	18

* First date of analysis.

Figure 3: Case study sites used in Anderson (1987a) to compute a snow melt onset algorithm.

melt date (Julian day 123) and the latest (Julian day 171). The East Siberian Sea site had an even greater variation of 74 days. Other first-year ice locations are much more consistent between the onset of melt dates. Multiyear ice locations also show variations between years, though they are smaller than the first-year ice locations.

Conclusions and Future Prospects

Sea ice is a critical component of the spring Arctic climate because it influences albedo and controls energy transfer across the OAH. The onset of snow melt is marked by a rapid increase in energy absorption as albedo decreases, harboring the coming seasonal melt. This paper outlined the utility of using space-

borne passive microwave remote sensing to derive important sea variables during the spring period. It presented basic concepts of microwave interaction theory, and it noted some of the important spaceborne passive microwave remote sensing instruments. This paper explained the derivation of sea ice extent, concentration, and snow melt onset, and it provided comments on the accuracy and precision of the remote estimates, with special attention to sources of error.

The continued launching of satellites such as SSM/I ensures that a long, continuous data record will be accrued, while the development of new sensors, such as the Advanced Microwave Scanning Radiometer (AMSR), promises to provide better spatial resolution. Continued algorithm development promises to provide

better precision and accuracy to the remote sensing estimation of spring-time sea ice variables. Understanding and characterizing results from this newer generation of satellites and algorithms may hold the potential to define the role of sea ice in Earth's climate with greater precision. ■

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