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# Evaluation of summer passive microwave sea ice concentrations in the Chukchi Sea based on KOMPSAT-5 SAR and numerical weather prediction data

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A B S T R A C T

Satellite passive microwave (PM) sensors have observed sea ice in Polar Regions and provided sea ice concentration (SIC) data since the 1970s. SIC has been used as a primary data source for climate change prediction and ship navigation. However, the accuracy of PM SIC is typically low and biased in summer. To provide more accurate information for climatic research and ship navigation, it is necessary to evaluate quantitatively the accuracy of PM SIC and to account for its errors. In this research, we evaluated the SIC data derived from PM measurements using four representative sea ice algorithms: NASA Team (NT), Bootstrap (BT), Ocean and Sea Ice Satellite Application Facility (OSISAF) hybrid, and Arctic Radiation and Turbulence Interaction STudy (ARTIST) Sea Ice (ASI). Analyses were performed for the Chukchi Sea in summer using KOrean Multi-Purpose SATellite-5 (KOMPSAT-5) Enhanced Wide-swath synthetic aperture radar (SAR) images. Ice/water maps were generated by binary classification of texture features in the SAR images based on Random Forest, a rule-based machine learning approach. SIC values estimated from the sea ice algorithms showed good correlation with those calculated from the KOMPSAT-5 ice/water maps, but the root mean square error was larger than 10%. SIC values estimated from the algorithms showed different error trends according to the KOMPSAT-5 SIC range. All algorithms overestimated SIC values in open drift ice zones (KOMPSAT-5 SICs ranged from 0% to 15%). In marginal ice zones (SICs ranged from 15% to 80%), the OSISAF SIC values were the least biased compared to those from KOMPSAT-5. The NT algorithm largely underestimated SIC values in marginal ice zones, while the BT and ASI algorithms overestimated them considerably. All algorithms, except for BT, underestimated SIC in consolidated pack ice zones (SICs ranged from 80% to 100%). By analyzing the correlations of biases of SIC from the algorithms with the numerical weather prediction (NWP) data from the European Reanalysis Agency Interim reanalysis, it was found that the overestimation of NT and ASI SICs was largely influenced by atmospheric water vapor content, while the underestimation of NT and OSISAF SICs was owing to ice surface melting. The overestimation of BT SICs was not significantly correlated with the NWP data. The underestimated SIC from the BT and ASI algorithms for high SIC regions might be compensated by the atmospheric water vapor content. The differences in SIC values estimated from each algorithm were due to different sensitivities to atmospheric water vapor content in the regions with KOMPSAT-5 SIC lower than 40% and to ice surface melting in the regions with higher KOMPSAT-5 SIC.

## 1. Introduction

Arctic sea ice is an important factor in the global climate system. The rapid decrease in the Arctic sea ice extent is a significant indicator of global warming (Johannessen et al., 2004; Screen and Simmonds, 2010; Kay et al., 2011; Mahlstein and Knutti, 2012; Stroeve et al., 2012). Moreover, the change in Arctic sea ice extent influences biological habitats and human activities in the region (Arrigo et al., 2008; Grebmeier et al., 2010; Ho, 2010; Kovacs et al., 2011; Inoue et al., 2015). As the most rapid change in Arctic sea ice extent typically occurs in summer and autumn (Holland et al., 2006; Comiso et al., 2008; Zhang et al., 2008; Overland and Wang, 2013), it is vital to observe sea ice during these seasons. Since the 1970s, passive microwave (PM) sensors have made observations of Arctic and Antarctic sea ice distributions based on the distinct microwave radiation properties between sea ice and open water. These observations have provided daily sea ice concentration (SIC) values, which are defined as the ratio of sea ice-covered area to the total area under consideration, with a grid size

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of 3–25 km (Steffen and Schweiger, 1991; Comiso et al., 1997; Markus and Cavalieri, 2000; Comiso et al., 2003; Andersen et al., 2007; Spreen et al., 2008). SICs derived from PM measurements have been used for the estimation of sea ice area and extent (Cavalieri and Parkinson, 2012; Ivanova et al., 2014), and currently serve as the primary data source for research on global climate change (Vinnikov et al., 1999; Vihma, 2014; Swart et al., 2015) and ship navigation (Khon et al., 2010; Y. Kim et al., 2014).

The Special Sensor Microwave Imager/Sounder (SSMIS) onboard the Defense Meteorological Satellite Program (DMSP) satellites (Kunkee et al., 2008), and the Advanced Microwave Scanning Radiometer-2 (AMSR2) onboard the Global Change Observation Mission-Water (GCOM-W) satellite (Imaoka et al., 2010; Okuyama and Imaoka, 2015) are representative PM sensors that have been observing sea ice since 2008 and 2012, respectively. The SSMIS continues the missions of the Special Sensor Microwave/Imager (SSM/I), while the AMSR2 is a replacement and successor of the Advanced Microwave Scanning Radiometer (AMSR) and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), respectively. There are many algorithms for the estimation of SIC from PM measurements. Among them, the NASA Team (NT) algorithm (Cavalieri et al., 1984) and a hybrid algorithm (Breivik et al., 2001; Tonboe et al., 2016) based on the Bristol (Smith, 1996) and Bootstrap (BT) frequency mode (Comiso, 1986; Comiso et al., 1997) have operationally been used for the estimation of SIC from SSMIS measurements at the National Snow and Ice Data Center (NSIDC) and the European Organisation for the Exploitation of Meteorological Satellites (EUMESAT)'s Ocean and Sea Ice Satellite Application Facility (OSISAF), respectively. For operational estimates of SIC using AMSR2 measurements, the Japan Aerospace Exploration Agency (JAXA) uses the BT algorithm (Comiso, 1986) as a standard algorithm. The Institute of Environmental Physics (IUP) at the University of Bremen and the Integrated Climate Data Center (ICDC) at the University of Hamburg have provided operational AMSR2 SIC products using the Arctic Radiation and Turbulence Interaction STudy (ARTIST) Sea Ice (ASI) algorithm (Spreen et al., 2008), which was developed based on high frequency channels of PM sensors. The IUP has also provided BT SIC products based on AMSR2 measurements.

Many studies have evaluated the SICs estimated from such operational sea ice algorithms using satellite optical and synthetic aperture radar (SAR) images. The NT SICs have been typically underestimated during the Arctic summer (Lubin et al., 1997; Belchansky and Douglas, 2002; Markus and Dokken, 2002; Meier, 2005). Although BT SIC values are typically higher than NT SICs, they have generally been underestimated in the summer season compared to optical and SAR image-derived SIC values (Belchansky and Douglas, 2002; Meier, 2005). The OSISAF algorithm typically retrieves erroneous SIC values in summer (Tonboe et al., 2016). The performance of SIC retrievals from the ASI algorithm was evaluated as being similar to that of the BT algorithm (Spreen et al., 2008), showing a negative bias in the sea ice melting season (Ivanova et al., 2015; Zhao et al., 2015). Based on previous studies, most sea ice algorithms used for SIC estimation from PM measurements show significant inaccuracies in the Arctic summer. As varied channels with different footprints and sensitivities to atmospheric water content and surface emissivity are used, the algorithms can show different SIC estimation performances (Ivanova et al., 2015).

Medium-low resolution satellite optical images such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High-Resolution Radiometer (AVHRR) data have been widely used to evaluate sea ice algorithms owing to their wide coverage and low cost (Belchansky and Douglas, 2002; Meier, 2005; Cavalieri et al., 2006; Heinrichs et al., 2006; Cavalieri et al., 2010). However, the optical images are limited by weather conditions and sun altitude; thus, it is very difficult to ensure a high success rate of obtaining cloud-free images with high sun elevation. Moreover, they have a spatial resolution of 500–1000 m in visible wavelengths, which cannot detect sea ice in small sizes, especially during the peak melting summer season when ice floes are fragmented. SAR, an active remote sensing system using microwave, can observe sea ice regardless of weather conditions and sun altitude (Zakhvatkina et al., 2013; Dabboor and Geldsetzer, 2014; Leigh et al., 2014; Han et al., 2016; Han et al., 2017). Current SAR satellites can observe wide areas of a few square kilometers with high spatial resolution, which can supplement the limitations of the medium–low resolution satellite optical images.

As Arctic sea ice extent decreases dramatically (Comiso et al., 2008; Cavalieri and Parkinson, 2012), the necessity for research on the evaluation of PM SIC data around the Northern Sea Route has been emphasized to enable the discovery of more economical, faster, and safer sailing routes. Sea ice in the Chukchi Sea exhibits an earlier onset of thawing in spring and a later onset of freezing in winter, than do other regions in the Arctic Ocean (Woodgate et al., 2010). This is because the heat from the Pacific Ocean is continually transported to the Chukchi Sea through the Bering Strait. This flow moves older sea ice northwards to be replaced by newly formed ice and warms the region. Such process has intensified in recent years and has contributed to dramatic changes in the extent of sea ice and even to its thickness in the Chukchi Sea (Maslanik et al., 2007; Comiso, 2012; Stroeve et al., 2012). The heat uptake from the Pacific Ocean and warm winds from the south tend to transport water vapor into the Chukchi Sea (Serreze et al., 2016). This impacts brightness temperature of open water measured by the PM sensors and causes retrieval of erroneous SIC values (Gloersen and Cavalieri, 1986; Andersen et al., 2006; Shin et al., 2008). Meanwhile, the warm conditions in summer in the region can promote sea ice melting, which is a major source of SIC underestimation from PM measurements (Cavalieri et al., 1990; Comiso and Kwok, 1996; Ivanova et al., 2015; Kern et al., 2016). Moreover, based on the regional characteristics of sea ice in the region, the Chukchi Sea is the terminus of the Northern Sea Route, where many vessels sail in summer by laying a route using PM SIC products retrieved from the algorithms. However, only a few studies have evaluated SIC products in this region.

The sea ice variability in the Chukchi Sea is closely linked to local climate change (Overland et al., 2011; Stroeve et al., 2014) and the PM SIC products have been used as a primary data to investigate the sea ice variability (Cavalieri et al., 2003; Comiso et al., 2008; Cavalieri and Parkinson, 2012). Therefore, it is necessary to evaluate the accuracy of the PM SIC products in the Chukchi to support climate research and to benefit shipping. Furthermore, the PM SIC values derived from the algorithms have accuracy that varies according to the ranges of the values. This is because of different sensitivities of the algorithms to atmospheric effects and to ice surface conditions by the range of SIC values (Comiso et al., 1997; Ivanova et al., 2015). The weekly ice charts provided by the Russian Arctic and Antarctic Research Institute (AARI) show that the range of SIC values in the Chukchi Sea in summer (Fig. 1a) is typically wider than in winter (Fig. 1b). Therefore, thorough verification of the accuracy of the PM SIC is required for the various ranges of SIC for the region in summer.

In this study, we evaluated SICs estimated from four sea ice algorithms implemented for PM measurements, namely NT, BT, OSISAF, and ASI, using high resolution ice/water maps with high accuracy derived from KOrean Multi-Purpose SATellite-5 (KOMPSAT-5) SAR images obtained in the Chukchi Sea of the Arctic Ocean in summer. SIC values were calculated from the KOMPSAT-5 ice/water maps, which were then compared with those from the algorithms. The differences in SICs derived from KOMPSAT-5 and the sea ice algorithms were analyzed statistically using different ranges of SIC values. The relationships between the biases from the algorithms and numerical weather prediction data were analyzed in order to investigate influences of atmospheric effects and ice surface conditions on the SIC values. Section 2 presents the data used in this research. Section 3 describes the methodology for the generation of ice/water maps from the KOMPSAT-5 SAR images and for the evaluation of the SICs estimated from the sea ice algorithms. Section 4 presents the results and discussion, and Section 5 concludes this paper.