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SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone

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A R T I C L E I N F O

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A B S T R A C T

Brightness temperatures at 1.4 GHz (L-band) measured by the Soil Moisture and Ocean Salinity (SMOS) Mission have been used to derive the thickness of sea ice. The retrieval method is applicable only for relatively thin ice and not during the melting period. Hitherto, the availability of ground truth sea ice thickness measurements for validation of SMOS sea ice products was mainly limited to relatively thick ice. The situation has improved with an extensive field campaign in the Barents Sea during an anomalous ice edge retreat and subsequent freeze-up event in March 2014. A sea ice forecast system for ship route optimisation has been developed and was tested during this field campaign with the ice-strengthened research vessel RV Lance. The ship cruise was complemented with coordinated measurements from a helicopter and the research aircraft Polar 5. Sea ice thickness was measured using an electromagnetic induction (EM) system from the bow of RV Lance and another EM-system towed below the helicopter. Polar 5 was equipped among others with the L-band radiometer EMIRAD-2. The experiment yielded a comprehensive data set allowing the evaluation of the operational forecast and route optimisation system as well as the SMOS-derived sea ice thickness product that has been used for the initialization of the forecasts. Two different SMOS sea ice thickness products reproduce the main spatial patterns of the ground truth measurements while the main difference being an underestimation of thick deformed ice. Ice thicknesses derived from the surface elevation measured by an airborne laser scanner and from simultaneous EMIRAD-2 brightness temperatures correlate well up to 1.5 m which is more than the previously anticipated maximal SMOS retrieval thickness.

1. Introduction

The recent strong decline of Arctic sea ice not only substantiates concerns about human-generated global warming and associated weather extremes but also raises interest in Arctic shipping and the need for operational sea ice forecast system. Sea ice thickness is one of the key parameters needed both for the initialisation and for the validation of forecast models (Day, Hawkins, & Tietsche, 2014; Yang et al., 2014). It can be derived from the freeboard conversion using altimetry (e.g. from CryoSat-2) or from microwave radiometry at low frequencies (Laxon et al., 2013; Ricker, Hendricks, Helm, Skourup, & Davidson,

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2014; Kwok & Cunningham, 2015; Kaleschke, Tian-Kunze, Maaß, Mäkynen, & Drusch, 2012). One major advantage of microwave radiometry is the wide swath coverage that allows daily sampling of large parts of the Arctic. The two retrieval techniques are complementary because the freeboard method has a large relative uncertainty for thin ice while the radiometric approach is not sensitive for ice thicker than the penetration depth of the electromagnetic waves in the ice medium. This maximum ice thickness depends on the liquid brine concentration in the ice and thus on the ice salinity and temperature. At the SMOS frequency of 1.4 GHz the maximum thickness was estimated to be less than half a meter for homogenous Arctic level ice (Kaleschke, Maass, Haas, Heygster, & Tonboe, 2010). The SMOS mission was originally proposed for estimating surface soil moisture and sea surface salinity but significant research progresses were also expected over the cryosphere (Kerr et al., 2001).

An algorithm developed at the University of Hamburg (UH) is based on a combined thermodynamic and radiative transfer model which accounts for variations of ice temperature and ice salinity (Tian-Kunze et al., 2014; Mecklenburg et al., 2016). The UH algorithm further accounts for an assumed lognormal shape of the statistical thickness distribution which results in a two to threefold maximum mean thickness up to 1.5 m. An empirical algorithm developed at the University of Bremen (UB) is based on training data obtained from ice growth models (Huntemann et al., 2014). The validation of the UB and UH SMOS sea ice thickness data products so far was limited to sparsely available ground truth and considerable uncertainties remained (Kaleschke et al., 2013; Maaß et al., 2015). A main limitation is the applicability of the SMOS sea ice thickness retrieval methods to cold seasons and excludes its use during melting periods.

A dedicated field campaign was conducted in the Barents Sea in March 2014 and gained a substantial amount of new validation data over thin ice. The new validation data comprises measurements from a helicopter based on RV Lance and the research aircraft Polar 5 operated from Longyearbyen airport, Spitsbergen. Sea ice thickness was measured using an electromagnetic induction (EM) system from the bow of RV Lance (Haas, 1998) and another EM-system towed below the helicopter (HEM) (Haas, Lobach, Hendricks, Rabenstein, & Pfaffling, 2009). Polar 5 was equipped among others with a laser scanner (ALS) used to determine sea ice freeboard and the radiometer EMIRAD-2 that measured the fully-polarimetric 1.4 GHz brightness temperature at nadir and tilted at 45°. This paper will provide an overview of the campaign and will present first results of the validation of SMOS sea ice thickness products. We thereby assume the ship-based and airborne measurements as “ground validation data” to assess the quality of the SMOS sea ice thickness retrievals. Furthermore, we show an example application of ship route optimization based on the results of a sea ice model forecast initialized with SMOS and AMSR2 data.

One important goal of the RV Lance cruise was to test this newly developed ice route optimization system which predicts the most efficient route in terms of safety and timesaving for ships navigating in ice infested Arctic waters. The system is based on a high resolving coupled Atmosphere–Sea Ice–Ocean model predicting ice thickness and concentration. These data are used by a software calculating time optimized routing alternatives. Because predicted data are used the ship's guidance is not only based on the ice situation observed in advance of the cruise but also on changes to be expected during the cruise. A main goal of the cruise was to validate the ice route optimization system's performance by passing through the proposed ice routes while assessing the relation of ship's performance and ice conditions, by comparing predicted travel duration with achieved duration, and, in some cases, by trying out what happens when a proposed redirection was ignored. No in-situ ice and snow measurements have been performed because they would have interrupted the test of the ice route optimization system.

The paper is organized as follows. The following section describes the sea ice condition and the set-up of the field experiment in the Barents Sea. The measurements and choice of parameters used to derive the sea ice thickness retrieval are summarized in Sections 3 and 4. The application of the SMOS data for sea ice forecast and ship route optimization is described in Section 6. In Section 5 the results of the comparisons are presented and discussed. The last section concludes the paper.

The aim of this paper is to describe the state and performance of SMOS sea ice retrieval algorithms based on the SMOS Level 1C data version V5.05 available during the experiment in March 2014. Improvements based on experience with the validation data acquired during this and other campaigns and with more recent SMOS data versions as well as the combination of SMOS and CryoSat2 (Kaleschke et al., 2015) are subject for subsequent papers.

2. Physical conditions and experimental set-up

The main experimental area between Edgeøya and Kong Karls Land in the east of Svalbard belongs to the Barents Sea which in most years features only a seasonal ice cover despite its high latitude (Smedsrud et al., 2013). The boundary between the relatively warm water brought through the Norwegian Atlantic Current and the cold East Spitsbergen Current defines the oceanic Polar Front (Pavlova, Pavlov, & Gerland, 2014). The climatological minimum winter sea ice extent was given as the latitude of 77°N (Sandven, Johannessen, Miles, Pettersson, & Kloster, 1999). However, the physical conditions between the second half of January to the first half of March 2014 deviated strongly from the climatology. The air temperature measured at Hopen Island meteorological station was on average 9 °C to 12 °C above the climatological value as defined for the period of 1961 to 1990 (Strübing & Schwarz, 2014). Southerly winds pushed the sea ice at the coast between Barentsøya and Nordaustlandet and only a relatively small strip of compacted ice remained at the beginning of the experiment (Fig. 2).

A comparison of historical hydrographic data over the years 1923–2011 with 33 CTD-measurements (Conductivity, Temperature, Depth) conducted during the RV Lance cruise revealed an anomalously northern location of the Polar Front in March 2014 (Dobrynin & Pohlmann, 2015). Significantly warmer (by up to 3.8 °C) and saltier (by up to 2.49 g/kg) conditions were observed in 2014 for nine out of ten stations in a point by point comparison with historical stations in 1983 and 1986. The surface salinity was measured covering the Atlantic and Arctic water masses on both sides of the Polar Front: in the Storfjorden Trench (approximately 35.05 g/kg) and in the Olga Basin south of Kongsøya (approximately 34.60 g/kg). During the main experimental phase between March 16 and March 27 the air temperature at Hopen was about 5 °C above the climatological mean. The near-surface air temperatures varied between −10 °C to −15 °C and caused new ice growth in the area of investigation. The anomalous ice retreat together with the subsequent refreezing created the perfect conditions to acquire sea ice thickness validation data over thin ice.

An array of 15 ice drift buoys was deployed from an aircraft before the ship cruise to measure the ice movement. The drift trajectories from the buoys are useful to determine the origin of the ice and help to determine if thickness changes are caused by ice dynamics or ice growth and melting (Figs. 2 and 3). In addition to 11 Cosmos-Skymed and 8 Radarsat scenes 83 TerraSAR-X images have been acquired in the new experimental 6-beam wide-swath mode to support the interpretation of the field data and to validate ice motion algorithms.

3. Sea ice thickness from electromagnetic induction

Electromagnetic induction (EM) measurements rely on the large contrast in electrical conductivity between sea ice and seawater. An electromagnetic field generated by a transmitter coil induces electrical eddy currents mainly in the seawater below the ice. A second receiver coil measures the secondary field produced by the eddy currents. The ratio of the secondary to the primary field depends on the height of the coils above the sea surface. Ice thickness can be calculated when