L-Band Radiometry for Sea-Ice Applications

Georg Heygster[1],
Stefan Hendricks[2], Lars Kaleschke[3], Nina Maass[3], Peter Mills[1],
Detlef Stammer[3], Rasmus T. Tonboe[4], and Christian Haas[5]

1) Institute of Environmental Physics, University of Bremen, Germany
2) Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany
3) Institute of Oceanography, University of Hamburg, Germany
4) Danish Meteorological Institute, Copenhagen, Denmark
5) University of Alberta, Edmonton, Canada

Executive Summary

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1 Introduction

Sea ice plays a significant role in the global climate. Monitoring both its extent and exchange processes is the challenge facing us in an uncertain twenty-first century. Passive microwave sensors have been used for over 30 years for this task. Amongst their advantages are frequent, global coverage in most weather conditions, and a lengthy record.

The ESA mission SMOS (Soil Moisture and Ocean Salinity) is now about to launch. It will extend the lower end of the observed microwave spectrum from currently 6.9 GHz down to the L-band (1.4 GHz). SMOS is unique in measuring in the L-band range at 1.4 GHz, the first continuously operating passive instrument to do so. As the angular field of view (FOV) of an antenna is directly proportional to the frequency and inversely proportional to the effective aperture area, the horizontal resolution would be much lower compared to exisiting microwave observations. However, by using a broad array of antennas that fold out upon deployment, SMOS will nonetheless have a horizontal resolution comparable to other microwave radiometers despite operating at a much lower frequency. SMOS will also be capable of detecting all four components of the Stokes vector.

Although explicitly being devoted to observation of soil moisture and ocean salinity, SMOS will also render information, when, during its polar orbit, it is pointing at the cryosphere instead. In order to gain insight already before launch in the potential of extracting geophysical information about the cryosphere from the SMOS signals, ESA has initiated a study (Heygster et al., 2009) to explore the potential of the spaceborne, polar orbiting L band radiometer for the retrieval of sea ice parameters by three means, (1) with a field campaign, (2) with a set of emissivity models used to analyze the campaign data and to generalize them to a broader range of environmental and experimental conditions than found during the campaign, and (3) with an investigation on using regions of the open ocean with cold surface temperature for an additional external sensor calibration.

2 POL-ICE Campaign

The field campaign took place in March 2007 in the North Baltic Sea as an add-on to the POL-ICE campaign. The thickness was measured with the airborne electromagnetic probe EM-Bird of AWI, carried by a helicopter. The L-band microwave signal was observed in coordinated flights of the EMIRAD radiometer of the Technical University of Denmark, carried aboard the Sky Van airplane of the Helsinki University of Technology. Figure 1 gives an overview over the coordinates flights.

3 Emissivity models

Two types of emissivity models have been used: first, several versions of so-called three layer models, describing the sea ice by just one layer, plus one layer for the atmosphere and one for the ocean. The three-layer models are specific for L-band, with just one constant sea ice permittivity. Second, multi-layer and multi-frequency models have been used. By physical modelling of the interaction mechanisms, they allow to cover the full microwave range from L-band to 100 GHz, namely MEMLS and the Strong Fluctuation Theory. As the wavelength is much larger than the size of the scatterers (air and brine inclusions), scattering can be neglected at L-band. This simplifies a lot the L-band only models. In addition to the Final Report, the modelling activities are documented in Kaleschke et al. (2009) and Mills and Heygster (2009).

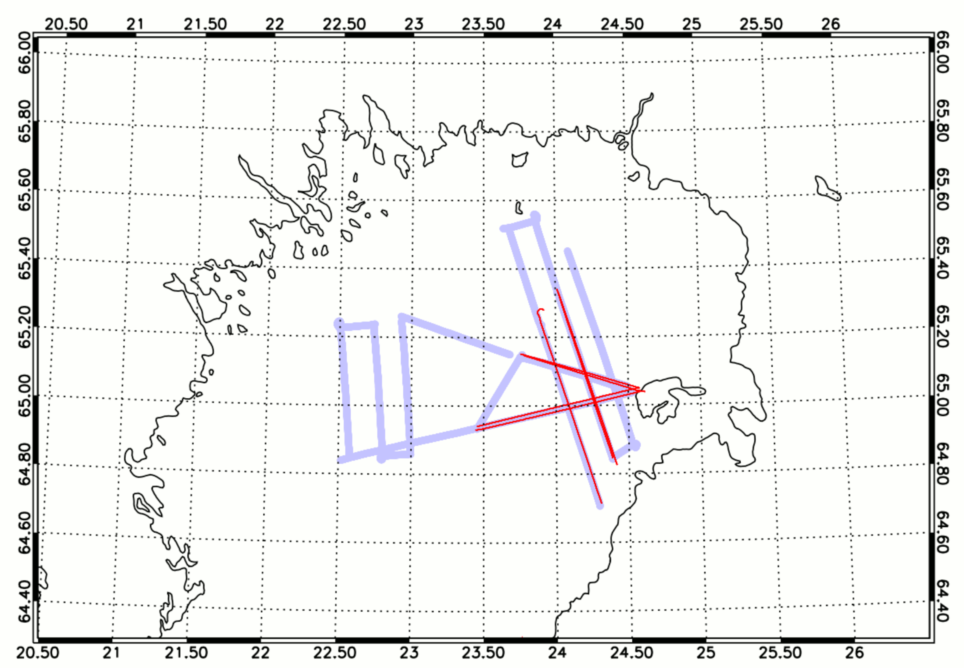

Figure 1: Coincident helicopter and aircraft flight tracks on March 12. and March 13. 2007 in the Bay of Bothnia. Helicopter flight tracks are marked by thicker lines, aircraft tracks by thinner lines.

Three-layer Models

The three-layer models consist of the layers air, sea ice and water, where within each layer all physical parameters are constant. This leads to a small number of parameters, namely incidence angle, thickness, sea ice concentration, temperature and salinity, and, via some parameterization, surface roughness.

With the first of the three-layer models, the brightness temperatures of a quality-selected subset of the campaign data can be prediced from the ice thickness with a standard deviation of about 7 K. Moreover, the model shows a reasonable sensitivity to thickness up to about 100 cm (Figure 2), and a one-channel retrieval, allowing for one separate retrieval based on each of the the vertically (TBv) and horizontally (TBh) polarized brightness temperatures, has been applied to a selected part of one of the POL-ICE flights with promising results (Figure 3), for details see Kaleschke et al. (2009).

The second three-layer model starts from the well-known fact that the salinity and thus the permittivity of thin Arctic sea ice vary with thickness. Real and imaginary part of the permittivity are constructed based on pairs of TBv and TBh observations of the POL-ICE campaign. Then, the model can be used to predict brightness temperatures from the permittivity. Two versions of this model have been used. In the first version, both real and imaginary part of the permittivity as function of sea ice thickness, are determined by empirical fits to the campaign data. In the second model, only the imaginary part is fit to the campaign values, and the real

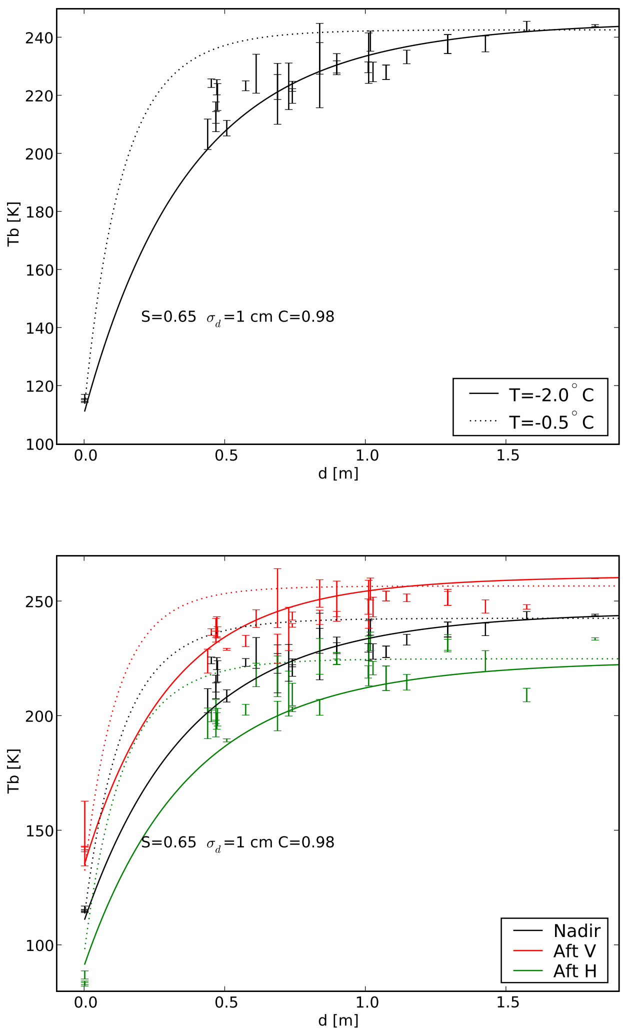

Figure 2: Modeled and observed brightness temperature. The upper graph is only nadir view, the lower figure contains also the data of the aft looking beam. The error bars represent the standard deviation of the brightness temperature for the according section of homogeneous thickness. The standard deviation of the difference of modeld and observed brightness temperature is about 7 K for all four channels. The solid (dotted) line is the modeled brightness temperature for -2 (-0.5) °C, respectively.

part is then determined using the Mixture Model, the empirical equations of Vant (1978b) and Hoekstra and Capallino (1971), allowing us to adjust for the higher salinity of the global ocean.

At temperatures near melting, the influence of ice concentration and ice thickness may be distinguished (Fig. 4), but at the same time retrieval of ice thickness becomes more uncertain because of the strongly increasing imaginary part of the permittivity. At low temperatures, the curves in Figure 4 again suggest a sensitivity of the brightness temperatures to thickness up to 50 cm, similar to Figure 2. This lower sensitivity to thickness at both higher salinity and higher temperatures is in agreement with the intuitive expectation because in both cases the salt content in the ice increases, which reduces the penetration dept. For young and thin sea

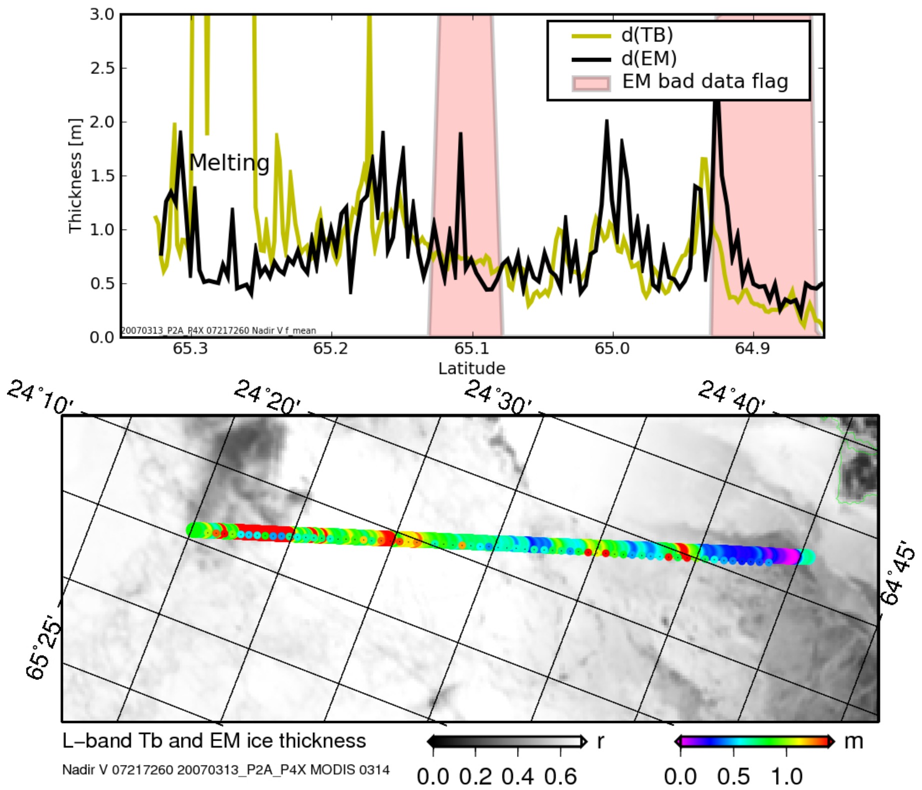

Figure 3: Thickness from Radiometer and EM from the flight of 13th March 2007. The upper graph shows the EM thickness with the thickness derived from the brightness temperature. The possible influence of the bathymetry is indicated with the red boxes. The lower graph shows the flight track and the color coded thickness overlaid on a MODIS image of 14th March 2007. The smaller dots indicate the helicopter EM and the larger dots the SkyVan EMIRAD measurements. The size of the footprints are not in scale. The EMIRAD and EM data was averaged over 200 and 100 samples, respectively.

ice, the condition of temperatures far below freezing, which is favorable for the detection of ice thickness, may be fulfilled at a reasonable percentage of the observed cases, e.g. during cold air outbreaks.

Multi-layer Multi-frequency Models

Multi-layer and multi-frequency models are much more sophisticated. In their view, the sea ice consists of a series of isothermal layers of snow and ice, each of them described by a set of ten parameters, like thickness, temperature, salinity, etc. In this study, an incoherent version of the Strong Fluctuation Theory (SFT) by Strogryn (1987) and the Microwave Emission Model of Layered Snowpacks (MEMLS, Wiesmann and Mätzler 1999) have been used. Both models include scattering and are validated up to 40 GHz (SFT) resp. 100 GHz (MEMLS). Output of a thermodynamic sea ice model, driven with ECMWF ERA 40 atmospheric data, served as input data for MEMLS. The sea ice model data at 85°N, 180°East over a complete winter season were used to simulate the L-band emission. Figure 5 shows the data set for first-year ice.

In a comparison study, these sea ice model data have also been used as input for the SFT

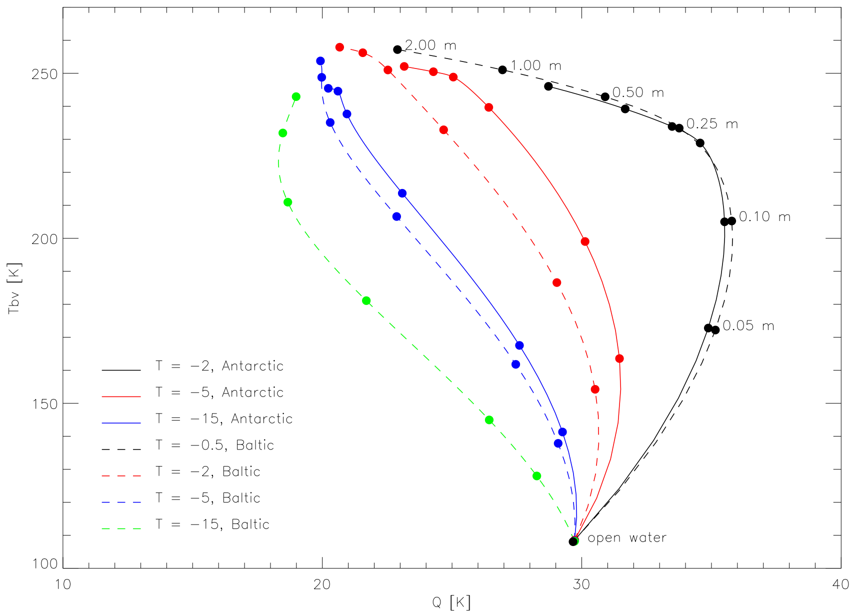

Figure 4: Model 2 curves for ice at different temperatures in the Baltic (S=5) and in the ocean (S=35).

and mixture model. Most of the models showed for first-year ice consistently a sensitivity of the emitted L-band radiation to thickness up to about 0.5 m (Fig. 6). The only exceptions are the mixture model where already at about 0.2 m saturation is reached, and the SFT, where the sensitivity reaches up to over 1 m. The sensitivity limit of about 0.5 m is also found for the campaign data when using the three layer model with constant permittivity.

4 Application Aspects

In future applications using the observed brightness temperatures, a careful analysis of the retrieval errors has to be performed since (1) the model parameterizations are imperfect, (2) the observations will have random errors, and (3) the effects of inhomogeneous ice parameters on the forward modelling and the retrieval have not yet been addressed. However, we have to expect that the ice conditions vary within the large footprint of about 50 km of the SMOS sensor. All model parameters, retrieved and input, need to be considered as effective parameters, averaged with some weight over the sensor's footprint. These parameters are sea ice concentration, thickness, temperature, salinity, roughness and other microphysical conditions.

On the other hand, each surface region will be observed several times during each overpass under different incidence angles. As a consequence, in this study the retrieval algorithms have been developed for all angles. The multiple observations at different incidence angles might be

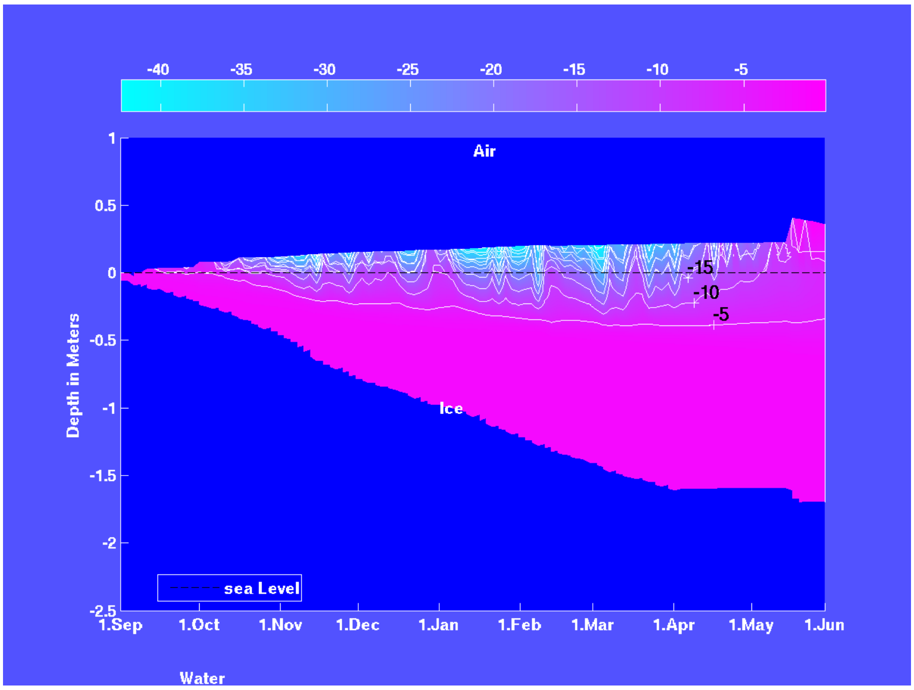

Figure 5: The temperature of first-year ice during winter at 85°N 180°E.

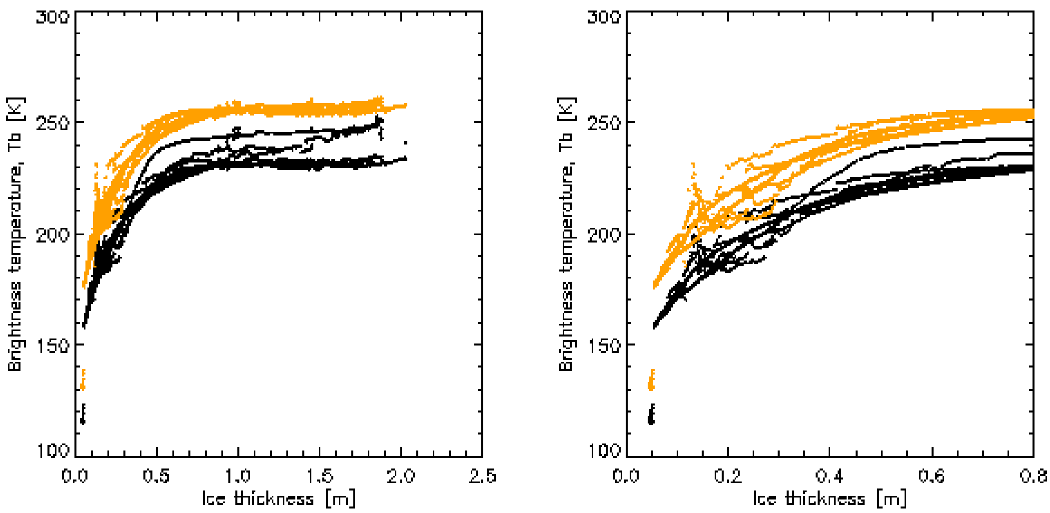

Figure 6: The TBv as a function of ice thickness for the simulated first-year ice profiles starting at September 1. and January 1. The black dots are the brightness temperature at nadir and the yellow dots are at 48deg. incidence angle. The profiles starting on September 1. typically reach thicknesses of 1.5-2m before May 31. The profile starting on January 1. reach about 1m before May 31. The left figure has different axis scaling.

used to determine additional quantities if their variation with incidence angle is strong enough. But as model calculations show, the observed brightness temperatures vary only little in the range of incidence angles of SMOS. Theefore, it is suggested to use multiple observations of a given scene to reduce the uncertainty in the retrieval by fitting a best retrieval to the observations at the various incidence angles.

The campaign data show that the contrast between open water is high enough to discriminate both surface types and to determine the sea ice concentration, and the empirical thickness -salinity relations observed in the Arctic have been confirmed, however with much scatter, for the Baltic where the salinity is much lower.

An additional explanation for the higher scatter in the Baltic might be found in some imperfections in the campaign data, both technical and physical, limiting their use for the intended purpose. The radiometer was not working stable during the flights, so that only few subperiods of the flights of stable radiometer functioning could be used for data analysis. Moreover, the temperature during the campaign was rather constant and near melting so that the sea ice emission could only be observed for a narrow range of temperatures. Finally, the salinity in the Northern part of the Baltic is much lower than that of the global ocean, influencing the sea ice properties and emission. In order to draw conclusions from the campaign results about the SMOS retrievals over Arctic sea ice, they must be transferred from Baltic to Arctic conditions using emissivity models, which is not obvious. Several more topics have been addressed in the study:

Numerical Values of Sea Ice Permittivity

As the sea ice permittivity is the most important quantity for emission modeling and model-based retrieval, it is interesting to compare its values found by and used in the different models. Using the thermodynamic sea ice model data in conjunction with MEMLS,the real part varies between 4.5 and 5.5, and the imaginary part between 0.1 and 0.5. For both the the SFT and the mixture model, the corresponding values are 3.5 to 7 and 0.002 to 1, a much larger range. The values determined from the campaign data range from 2 to 8 for the real part and from 0.03 to 0.1 for the the imaginary part (Heygster et al., 2009). Thus, the values for the Arctic and the Baltic are less different than expected, probably due to the high temperatures during the POL-ICE campaign.

Third and Fourth Stokes Components U and V

SMOS will be able to capture in addition to the first two components of the Stokes vector, which are the horizontally and vertically polarized brightness temperatures, the third and fourth component, called U and V. Two studies have been devoted to the higher Stokes components. First, a deviation of the sensor attitude from horizontal orientation will cause a crosstalk from the first two Stokes components to the third one, U. This influence has been quantified and compensated in the airborne data, demonstrating that in the campaign, up to about 60% of the observed U signal is caused be the aircraft attitude, and only 40% by geophysical influences. Second, a model of horizontally anisotrope permittivities generating nonzero U and V Stokes components has been developed.

External Calibration

Finally, an investigation for a region with stable temperature and salinity values of the high latitudes has been conducted where the surface temperature of the ocean could be used as an external calibration source for SMOS L-band radiances without adding any extra in situ observations. It has turned out that there is no location in the Greenland-Iceland-Norwegian Sea where SST is stable, and regions with low variability do not agree with regions of low SSS variability in a model simulation.

5 Conclusions and Recommendations

The sea ice emissivity models suggest a clear sensitivity of SMOS data to sea ice thickness. As on the other hand, during the POL-ICE campaign there have been several shortcomings, the assessment of the potential to retrieve ice thickness from SMOS data needs more effort. This requires a ground truth data set with known ice thicknesses at a horizontal extent comparable to the SMOS sensor footprint. The best way to obtain such data would be a dedicated field campaign. Ideally it would take place in a region of fast growing thin ice, at a horizontal scale comparable to the SMOS footprint. Candidate regions and seasons are

1. Sea of Ohotsk, January,
2. Ross Sea, April,
3. North of Siberia, October/November, and
4. Hudson Bay, December.

Note that these are just rough indications. The exact region and period would have to be determined for the individual year. Moreover, observations take at a broader range of temperatures will be favorable. But even without a dedicated campaign, the situation is not hopeless. A more economic way would be to use data of regions where the large-scale formation of sea ice is known a priori, e.g. from meteorological conditions (see list above) and recurring polynyas.

Without doubt additional information, especially about the ice temperature, will be helpful in the retrieval process. Therefore it is suggested to use the SMOS data in conjunction with other passive microwave sensors, e.g. AMSR-E, and with atmospheric circulation model data such as ECMWF. As sea ice salinity and roughness are difficult to determine from the SMOS observations alone, other informations like climatology and ocean model (deformation) can also be helpful to restrict the variability range of retrieved quantities. It has become obvious that the sea ice emissivity models need more development in order to meet the best tradeoff between complexity required to reflect the important physical feature, and at the same time to be sufficiently simple to be handled and understood.

During the commissioning phase of SMOS, the information content of the third and fourth Stokes components over sea ice should be investigated more in depth. The best way for an external calibration of SMOS L-band radiances seems to use data from the global SSS cal/val program, such as MW SST fields, drifter, ARGO floats plus estimates of wind and humidity.

The promising results of the project are that SMOS will have some potential for ice thickness and the lower boundary of ice volume retrieval. The sensitivity for Arctic ice thickness retrieval of up to half a meter is complementary to the capabilities of altimeter instruments. The thin ice plays an important role for heat exchange between the ocean and the atmosphere. Therefore, a SMOS based ice thickness product will be certainly useful for sea ice applications in climate research, meteorology, and perhaps even for operational services for the assistance of ship navigation in polar waters.

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