Tc-2016-273 – First review

This study shows the potential use of brightness temperature data from the ESA SMOS mission for forecast model assimilation, to improve sea ice thicknesses in thin ice regions. Although the application of brightness temperature data rather than a derived thickness product is not a new concept, this is the first time that the usefulness of SMOS data has been explored in detail and the manuscript will be of interest to the observation and modelling communities. However, I have some concerns to be addressed.

We would like to thank the referee for its initial positive assessment and will now discuss each point in detail.

The manuscript currently lacks a suitable level of transparency and detail regarding a.) the uncertainties associated with modelled brightness temperature…

As there are no derived uncertainties for the ORAP5 reanalysis product we use the uncertainties of the follow-on product ORAS5 and assume that they will be of same magnitude as the uncertainties of ORAP5. Both products have the same resolution and use the sea ice model LIM2. Following this comment, we added a new table (Tab. 2) to the manuscript in section 2 [p.5]. It shows the uncertainties compared with the monthly variation of the physical properties. The uncertainties are ten times smaller than the monthly variations except sea ice thickness. Moreover, we analyze the impact of uncertainties on the brightness temperature simulation for both models in an additional table [p.13]. The results show a large impact of sea ice thickness uncertainties on the brightness temperature simulation and far less influence by all other variables.

… and b.) the limitation of ORAP5 data in the development of a reliable brightness temperature model.

This paper does not follow the purpose to identify one of the radiative transfer models to be the correct one as the uncertainties from the reanalyzes are still noticeable, especially in the intermediate range of first year sea ice thicknesses. However, we do give a recommendation for one of the models to be more suitable for brightness temperature assimilation. This recommendation however is only based on the open water case and the saturated case over very thick sea ice, where uncertainties of sea ice concentration and sea ice thicknesses do not count. As this has been misunderstood we added a clarification in the revised version and specifically note that this is the case.

… The authors should briefly explain how each of these parameters is derived in ORAP5 and state their associated uncertainties. ..

Added to the methods. [p. 4, line 25 ff.]

Based on this they should expand on why using a radiative transfer model (which is itself developed from derived parameters) as a forward operator in a brightness temperature assimilation scheme for thin sea ice thicknesses is preferable to using observed thickness data.

Please note that also "observed sea ice thickness" products from SMOS over thin sea ice rely on radiative transfer models to derive sea ice thicknesses from brightness temperatures. Therefore in any case, there is always the uncertainty of an imperfect radiative transfer model. However, the advantage of a direct brightness temperature simulation is the availability of a coherent set of input data from the reanalyzes/forecast model. This allows us, for example, to take into account the sea ice concentration in our calculations which as not been possible before (Tian-Kunze, 2014). Furthermore, snow thicknesses are directly derived in the forecast model and are not taken from a general annual climatology. Another advantage of a brightness temperature assimilation is a better traceability of the errors as all variables belong to the same dataset. However, since this point led to confusion we added another sentence to section 1. [p. 2, lines 31-33]

An easy and effective way to do this would be to tabulate the effects of the sensitivity study for both models. What effect (expressed as a percentage, for example) does varying each parameter to its minimum and maximum simulated value have on brightness temperature over thinner (say 10 cm) and thicker (say 50 cm) sea ice?

We followed this idea and added another table to the results section [p. 13, table 2]. It shows the propagating error in brightness temperatures based on the ORAS5 uncertainties. The error is expressed in Kelvin for each quantity provided by ORAP5. The dominating uncertainty (more than 80% of all variables) over first year sea ice is based on the sea ice thickness. We conclude that as beneficial for the brightness temperature assimilation for sea ice thicknesses. Most brightness temperature differences will be due to sea ice thickness and can thus be corrected, whereas the other parameters have a minor impact. Note that the sea ice concentration over first year sea ice only shows an average uncertainty of 5%.

P1 L4: It is perhaps more accurate to state that SMOS brightness temperatures have been proven to be valuable in estimating modal thin sea ice thicknesses, not mean. See for example [1].

Changed in revised version.

P3 L30: Why 2 m? 2 m is 0.5 m greater than the maximum SMOS validation thickness

We reprocessed all results with a maximum sea ice thickness of 1 meter to account for thinner first year sea ice. The changes are almost negligible that will not alter the results. However, the new figures are included in the revised version.

P5 L27: The assumption of dry snow is oversimplified. Despite this being a necessary assumption made for the model, the authors should comment on the potential impacts of a wet snow layer on brightness temperature. This is especially important, as wet snow is most common on thin FYI, such as that measured by SMOS, even in winter.

Carsey 1992 examined the influence of wet snow above saline ice on brightness temperatures (Carsey 1992, Fig. 4-26). He does not see a significant influence on brightness temperatures at 10 GHz, even more decreasing at lower frequencies. The snow moisture is described to be below 2% if the temperatures are at 268K or lower, up to 3% if the temperature is greater than 273K (Carsey 1992, Fig. 16-2). Therefore the penetration depth will be at least 1 meter and should be negligible at 1.4 GHz.

P6 L8-19: The relevance of the brief introduction to NEMO and LIM would not be clear to someone who is unfamiliar with ORAP5. I believe ORAP5 was produced from these models, but this is not explicitly stated in the manuscript.

Considered in revised version. [p. 4, lines 24]

Conclusion: A comment on the potential for a similar approach over thick ice would be useful. If brightness temperature can't be used, what could?

A common method to derive thick sea ice thicknesses is by using altimetry of e.g. ICESat or CryoSat-2 (Kwok et al. 2009, Laxon et al. 2013). By measuring the elevation of the sea ice surface above the water line (called freeboard) it is possible to estimate ice thicknesses above 1 m. However, systematic errors are introduced by using e.g. a snow thickness climatology or fixed snow density (Kwok 2014, Ricker et al. 2015). Thus, a similar approach to this study might improve the accuracy of the freeboard calculation by using the reanalyzes data as input. In future, even a synergy of SMOS thin and altimetry thicker sea ice thickness derivation might be feasible, as it already exists for the combined SMOS and CryoSat-2 sea ice thickness retrievals (Ricker et al. 2017).

Carsey, F. D. (1992). *Microwave remote sensing of sea ice*. American Geophysical Union.

Kwok, R.: Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard, Geophysical Research Letters, 41, 5014–5020, doi:10.1002/2014GL060993, http://dx.doi.org/10.1002/2014GL060993, 2014.

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003-2008, J. Geophys. Res., 114, doi:10.1029/2009JC005312, 2009.

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S., and Davidson, M.: CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophysical Research Letters, 40, 732–737, doi:10.1002/grl.50193, http://dx.doi.org/10.1002/grl.50193, 2013.

Ricker, R., Hendricks, S., Perovich, D. K., Helm, V., and Gerdes, R.: Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: An observational approach with buoy data, Geophysical Research Letters, 42, 4447–4455, doi:10.1002/2015GL064081, http://dx.doi.org/10.1002/2015GL064081, 2015GL064081, 2015.

Ricker, R., Hendricks, S., Kaleschke, L., Tian-Kunze, X., King, J., and Haas, C.: A Weekly Arctic Sea-Ice Thickness Data Record from merged CryoSat-2 and SMOS Satellite Data, The Cryosphere Discuss., doi:10.5194/tc-2017-4, in review, 2017.

Tc-2016-273 – Second review

General

With this work the authors achieved insight in several aspects of modelling and observing arctic sea ice with 1.4 GHz brightness temperature data from SMOS for November 2012 and March 2013. The key to the results is the coupling of a full set of models, consisting of meteorological forcing, sea-ice physics, microwave emission and comparison with observations. In spite of some inconsistencies, especially during the sea-ice growth phase, the results are encouraging. I am glad for these results. Congratulation! Exploration on what these results mean with respect to sea-ice research would be helpful. Unfortunately the text is often unclear, sometimes misleading or erroneous, the main reason why it took me a long time for writing this response. The authors should try to find a more appropriate title and better names for each section. Furthermore they should reduce the hand-waving explanations in words, and instead use the logic of mathematical formulations. Furthermore, there is a need for improving the language.

We would like to thank the referee for its initial positive assessment and will now discuss each point in detail.

Special - suggestions for improvements

1) Throughout the paper change from plural to singular (as already done in Table 2) for: - "sea-ice thicknesses" because there is only one thickness parameter for sea ice.
- "snow thicknesses", even better, use "snow depth".
- "sea-ice concentrations", unless you distinguish between different types of sea ice (e.g. first year, multi year).

We agree. The document has been revised and plural has been changed to singular. (multiple line numbers)

Special - suggestions for improvements

2) Section 2 "Data and Methods". This section is poor: - formally (longest part of Section 2 without any subsection, followed by short Subsections 2.1 and 2.2, and by a related Section 3)
- logically (models are not well presented, some parameters not defined, equations are missing, Figure 1 confusing, Table 1 inconsistent with text for brine volume fraction),
- with respect to the motivation for this paper (e.g. the multilayer model description starts with "The incoherent model used in Maaß et al. (2013) is based on", without any indication why this text is found here, and the same holds for the single-layer model). Start e.g. with "For our analysis we selected ... It is useful because ..."
- and details:

We believe the purpose of this manuscript is the application of the models but not the introduction of them. Therefore, we decided to drastically shorten and rearrange the method section about the radiative transfer models as basically everything is explained in the referenced papers which explain the models for sea ice purposes in detail. Therefore, we added a motivation, why we exactly used these two radiative transfer models. We changed the arrangement of the subsection, so there so no part without any subsection anymore. We dropped Figure 1 and Table 1 as they were confusing and already covered by the reference papers.

p. 1, line 22: The statement "Microwave radiation is especially useful to derive thin sea ice thicknesses as it is able to penetrate snow and sea ice for more than half a meter". This statement is incorrect because it is far too general. Microwave (1 to 300 GHz) penetration into sea ice is certainly much less than half a meter in most types of sea ice and it is marginal even at the lowest frequency.

Only microwave radiation at 1.4 GHz is investigated in this manuscript. We add this limitation to the revised manuscript to avoid confusion.

"Microwave radiation at 1.4 GHz is especially useful to derive thin sea ice thickness as it is able to penetrate snow and sea ice for more than half a meter and closes the gap to thicker sea ice thickness retrievals of more than 1 meter by using altimetry" [p1,lines 20-24]

p.3, line 6: ORAP5 seems to play an important role. A description would help, a proper reference is a 'must'.

The ORAP5 reanalyses product provides the input data for the radiative transfer models. A reference has been added in this sentence. [p 3, line 7]

p. 3, lines 14 - 15: What do you mean with "salinity ration"? (misprint?)

The sentence has been dropped in the process of reworking the manuscript. Before that, true, it was a spelling error.

p. 5, lines 3-4: Improve this part, but do not try to correct the galactic radiation nor let the atmosphere deviate. What do you mean?: "To account for corrections of the galactic background radiation and atmospheric deviations a simplified atmospheric model (Peng et al., 2013) is taken forced by..." And why do you use a simplified model? What kind of simplification? Use mathematics to show exactly what you did. Readers might want to check.

We used exactly the model describes in Peng et al. 2013 but only called it simplified. To avoid this misunderstanding in the future we dropped the word simplified and only called in the atmospheric model of Peng et al. 2013. [p4, Lines 11-13]

p. 5, line 17: What do you mean with "temperature insulation"? Do you mean "thermal insulation"?

Yes, will be changed in the revised document. [p3, lines 25-26]

p. 5, line 23 once more: "The incoherent model used in Maaß et al. (2013) is based on radiative transfer equations and describes the emitted radiation from a stratified bare soil". Please be more specific, e.g. by writing "... describes the upwelling brightness temperature at h and v polarisation from bare soil represented by plane-parallel layers with or without surface roughness".

Changed in the revised document with a minor correction as the model of Maaß et al (2013) does not take into account any surface roughness. Therefore, we used the same sentence with "… plane-parallel layers without surface roughness." [p3, Lines 27-29]

p. 5, line 27: The snow density selected seems to me rather high for the usually shallow snow layers found on sea ice. Why do you consider a fixed value?

The fixed value has been used as the sensitivity of snow depth on L-Band radiation is very low. Maass et al. 2013 showed in figure 3 that the sensitivity of snow density on brightness temperatures from 260 kg/m^3 up to 340 kg/m^3 is below 1 Kelvin. The value of 330 kg/m^3 has been used as Warren et al. (1999) suggest that value as the climatological average value for March over Arctic sea ice. This evidence has been added to the revised version of the manuscript. [p3, Lines 32-34]

p. 5, line 32 to p. 6, line 3: Modification of the model. Either describe exactly what you did or delete this part. Note that there is a risk of introducing errors.

We decided to rephrase this paragraph and make it shorter, less confusing. Therefore we adapted the whole paragraph.

3) Improve the description of all methods by using appropriate figures for explaining the geometry, angles, etc. as well as mathematical formulas at least for the relevant expressions to enable definitions of the coefficients mentioned (p. 3).

See rearranging of the methods section above. True, but as we only use the radiative transfer models we think there is no need for a comprehensive explanation of the mathematical formulas used as they are all already mentioned in the cited references.

4) p. 7, lines 3-5: Improve physics and timing in "In the melting season, when melt ponds form on sea ice and temperatures begin to rise". Note that temperature rise is much earlier than formation of melt ponds. Explain what you mean and improve the sentence that follows: " SMOS brightness temperatures over sea ice are impossible to connect to a specific sea ice property (Kaleschke et al., 2010)". The logic to the next sentence and its meaning are not clear: "Thus, November and March are the first and the last month, respectively, with full monthly data coverage from SMOS and therefore chosen."

Sentenced rephrased. We need to ensure to have both, cold temperatures and of course no melt ponds on the sea ice. This is the basis for the sea ice thickness assimilation. We now focus in the text on the cold temperatures.

"November and March are the first and the last month in which temperatures are below freezing in the winter season (Vikhamar 2016) and are therefore chosen." [p5, lines 8-11]

5) p. 7, line 15 - : Improve " chosen as values higher than that are not expected to be seen".

We rephrased and added an explanation as the physical maximum of brightness temperatures is capped by 273.15 Kelvin for a surface at 0°C if the emissivity would be at 1.

"Values higher than that are not expected to be seen in the Arctic between November and March as the physical maximum of a surface with temperature at the freezing point would be 273.15 K if the emissivity was 1." [p. 6, lines 1-3]

Also improve the following sentence: " The brightness temperature product consists of vertical and horizontal polarization, which are averaged up to 40 incidence ...". I do not understand. And what do you mean with the sentence that follows? " These brightness temperatures are said to represent L-Band measurements at nadir as brightness temperature changes that are connected to the varying incidence angles are expected to cancel out each other when both polarisations are considered."

The actual goal is not to have a product that represents nadir observations but to have measurements without angle dependency and as big as possible daily data coverage. In case of SMOS L-Band measurements this is achievable by averaging up to 40° incidence angle. We corrected that mistake and improved the sentences in the revised version.

"The brightness temperature product is provided at vertical and horizontal polarization. Although these measurements vary with incidence angles the intensity, defined as the average of horizontally and vertically polarised brightness temperatures, remains almost constant in the range of 0 to 40 degrees over sea ice. By averaging over this incidence angle range we obtain more brightness temperature data per grid point per day reducing considerably the uncertainty." [p. 6, lines 3-8]

6) p. 7 "Sea water correction" What do you mean? Please do not try to correct the water! Please first explain the purpose of this section, and then improve it, especially explain what Figure 2 is supposed to show. Its legend cannot be used to understand what the data clouds mean, nor is the caption of any help. Furthermore the quality of these data is not convincing due to the poor correlation shown. And there must be a reason for the Tb correction. Try to find the error.

We changed the title of the subsection, included it into the methods section and changed the first sentence towards a clearer statement that we apply the bias correction for brightness temperature above sea water only to exclude as many as errors for our brightness temperature comparison of sea ice as we can. This comparison is not supposed to be a main result of this study, but rather to increase the credibility of the brightness temperature comparison above sea ice.

The statement of a difference between simulated and measured brightness temperatures above sea water is a discovery, which we cannot explain by the analysis in this paper, nor can we physically. The error might be due to the representation of wind speed in the model or something totally different. The purpose here is only to have as little influence on the sea ice brightness temperature simulations as possible.

The caption of figure 2 has been reworked, now hopefully making a clearer statement about the information to see in the figure. [p.8]

7) p. 8 "Brightness temperature comparison". Give a motivation to the reader for not skipping this section. If it is a 'result' section, then please call it accordingly.

We renamed it Result section with subsections called “Brightness temperature comparison” and “Radiative transfer model sensitivity study”.

8) p. 10, line 1, also discussion p. 17-18: Explain what the "Kolmogorov-Smirnov-Test " is supposed to check and present the results properly. This is relevant because you use this information for the decision to drop one of the models used. Can you support this decision by physical arguments?

We dropped Figure 6 as it basically shows the same information as Figure 5 does. However, we still use the Kolmogorov-Smirnov-Test which is now briefly introduced in the Discussion section [p.15, line 35]. The result of the test is mainly determined by brightness temperatures over open water, as well as fully saturated brightness temperatures over thick sea ice. There, the MA2013 model overestimates brightness temperatures (already stated in the discussion).

9) p. 13, Figure 5: Nice representation. However the concentration of data points near the two main spots causes problems in the interpretation. It appears that the assessment of thin ice and medium ice concentration is difficult. Think about how to improve the situation, e.g. by omitting some of the data.

Unfortunately, there is no reliable data to make a proper assessment of thin ice and medium sea ice concentration. Therefore, we here decided to concentrate on the open water and 100% sea ice concentration case as it is common in sea ice concentration retrievals (Ivanova et al. 2015). These two cases are our only two reference points which we can use to make a statement about the quality of the radiative transfer models.

As this led to confusion we added another sentence to the discussion section where we make the statement about the favorable model. [p 15. Lines 13-15]

10) p. 13, lines 16-17: "we observe an underestimation of sea ice concentration" underestimation by what, i.e. which model?

By the reanalysis, has been changed in the revised version.

“Following, we observe an underestimation of sea ice concentration and an overestimation of sea ice thickness in the reanalysis over a range of two weeks, whereas the SMOS brightness temperature only deviate more than 20 K for 5 days.” [p. 14, lines 9-10]

11) p. 15, Figure 8: Exchange the two legends in order to be close to the respective y

axis, and clarify 'growth model' with respect to caption (Lebedev ?). What is the role "Lebedev" is playing here (missing in Sect 2).

A related subsection about the sea ice growth model from Lebedev has been added to section 2. The legend in Figure 8 has been exchanged.

References:

[Ivanova, N. , Pedersen, L. T., Tonboe, R.T., Kern, S., Heygster, G., Lavergne, T., Sørensen, A., Saldo, R., Dybkjær, G., Brucker, L. and Shokr, L.: Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations, The Cryosphere, 2015]

Arctic sea ice signatures: L-Band brightness temperature sensitivity comparison using two radiation transfer models

Friedrich Richter[1], Matthias Drusch[1], Lars Kaleschke[3], Nina Maaß[3], Xiangshan Tian-Kunze[3], and Susanne Mecklenburg[2]

[1]European Space Agency, ESA-ESTEC, 2200 AG Noordwijk, the Netherlands
[2]European Space Agency, ESA-ESRIN, Via Galileo Galilei, casella postale 64 - 00044, Frascati, Italy
[3]Institute of Oceanography, University of Hamburg, Bundesstraße 53, 20146 Hamburg, Germany

Correspondence to: Friedrich Richter (friedrich.richter@esa.int)

Abstract. Sea ice is a crucial component for short-, medium- and long term numerical weather predictions. Most importantly changes of sea ice coverage and areas covered by thin sea ice have a large impact on heat fluxes between the ocean and the atmosphere. L-Band brightness temperatures from ESA's ~~first~~ Earth Explorer SMOS (Soil Moisture and Ocean Salinity) have been proven to be a valuable tool to estimate ~~mean~~ thin sea ice ~~thicknesses~~thickness. Potentially, these measurements can be assimilated in forecasting systems to constrain the ice analysis leading to more accurate initial conditions and subsequently more accurate forecasts. As a first step, we use two different radiative transfer models as forward operators to generate top of atmosphere brightness temperatures based on ORAP5 model output for the 2012/2013 winter season. The simulations are then compared against actual SMOS measurements. The results indicate that both models are able to capture the general variability of measured brightness temperatures over sea ice. ~~We identify one model to be favorable for brightness temperature assimilation purposes in the ORAP5 setup.~~ The simulated brightness temperatures are dominated by sea ice coverage and thickness changes most pronounced in the marginal ice zone where new sea ice is formed. There we observe largest differences of more than 20 Kelvin over sea ice between simulated and observed brightness temperatures. We conclude that the assimilation of SMOS brightness temperatures yield high potential for forecasting models to correct for uncertainties in ~~sea ice thicknesses of less than 0.5 meter~~ thin sea ice areas and caution that uncertainties in sea ice fractional coverage may induce large errors.

1 Introduction

For the first time, the European Space Agency ~~second~~ Earth Explorer mission SMOS (Soil Moisture and Ocean Salinity) delivers brightness temperature measurements at 1.4 GHz on a global scale (Mecklenburg et al., 2012). SMOS L-Band brightness temperatures have been used to produce operational products of soil moisture over land (e.g. Albergel et al., 2011; Kerr et al., 2012) and ocean salinity over water areas (e.g. Reul et al., 2014) since 2010. Additionally, SMOS passive microwave imagery has been used to estimate sea ice parameters, such as sea ice ~~thicknesses~~ thickness (e.g. Kaleschke et al. (2012), Tian-Kunze et al. (2014)), sea ice ~~concentrations~~ concentration (e.g. Gabarro et al. (2016)) and snow coverage (Maaß et al., 2015). Microwave radiation at 1.4 GHz is especially useful to derive thin sea ice ~~thicknesses~~ thickness as it is able to penetrate snow and sea ice for more than half a meter and closes the gap to thicker sea ice thickness retrievals of more than 1 meter by using altimetry (Kwok and Cunningham, 2008; Kaleschke et al., 2010; Ricker et al., 2014; Tilling et al., 2016). This ~~feature appears to be especially important since~~ capability is especially important as the Arctic Ocean ~~is said to shift to~~ shifts to a new state, in which older, thicker sea ice ~~gets more and more~~ is being replaced by younger and thinner ice (Laxon et al., 2013; Meier, 2015).

Much effort has been made to validate L-Band based sea ice thickness retrievals. In preparation for SMOS, Kaleschke et al. (2010) showed a significant agreement between sea ice ~~thicknesses~~ thickness derived from L-band brightness temperatures and helicopter based electromagnetic induced (EM) sea ice measurements in the Bothnian Bay. After the launch of SMOS in 2009, the sea ice thickness retrieval has then been successfully validated with MODIS thermal infrared imagery data in the Kara and ~~Lepedev~~ Laptev sea (Kaleschke et al., 2012) and provided the first Arctic-wide map of thin sea ice thickness. ~~The retrieval algorithm is based on the radiative transfer model of Menashi et al. (1993) and has been extended by a sea ice roughness approximation (Kaleschke et al., 2010), a~~ (Kaleschke et al., 2010) applied a semi-incoherent radiatve transfer model Menashi et al. (1993) which was further extended with a thermodynamic sea ice model to consider variations of ice ~~temperatures and ice salinities~~temperature and ice salinity temperature and ice salinity, as well as a statistical sea ice thickness distribution (Tian-Kunze et al., 2014). Retrieved ice ~~thicknesses prove to correlate~~ thickness correlates with ship- and airborne observational ~~thicknesses~~ thickness up to 1.5 m (Kaleschke et al., 2016). However, as previous algorithms lack a comprehensive representation of the complex structures of sea ice, such as electromagnetic properties from multiple sea ice layers and a snow layer on top, a second radiative transfer model was utilized, namely the model used in Maaß et al. (2013) a modified version of the multi-layer model from Burke et al. (1979). The model has been used to derive snow ~~thicknesses~~ depth over thick multi-year sea ice (Maaß et al., 2013) but has not yet been applied to derive sea ice ~~thicknesses~~ thickness on an Arctic-wide scale.

A valuable application for sea ice observations is the assimilation into forecasting models. The assimilation of fractional sea ice coverage derived by remote-sensing techniques has been proven to be very beneficial and is conducted in ~~varies~~ various studies (e.g. Stark et al. (2008); Lindsay and Schweiger (2015)). The sea ice age derived from sea ice drift measurements from the National Snow and Ice Data Center (NSDIC) has been used as a proxy for sea ice ~~thicknesses~~ thickness in the Arctic Sea Ice Volume reanalysis Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) (Zhang and Rothrock, 2003). ~~Those sea ice thicknesses were~~ The sea ice thickness was compared with observations from e.g. airplanes, buoys and submarines, but not on a larger scale. However, the direct assimilation of Arctic-wide remote-sensing based sea ice ~~thicknesses~~ thickness has not yet been performed on a regular basis. As a first attempt, Xie et al. (2016) assimilated SMOS sea ice ~~thicknesses~~ thickness of less than 0.4 m ~~have been assimilated~~ in the TOPAZ Arctic Ocean reanalysis with the result of reduced Root Mean Square Deviations (RMSD) between ~~SMOS-Ice~~ SMOS and TOPAZ reanalysis sea ice ~~thicknesses~~ thickness in March and November (Xie et al., 2016). It has been found that the inconsistency between sea ice ~~concentrations in SMOS and the model~~ concentration of the model and the sea ice concentration based on SMOS data is one of the major limitations for a sea ice thickness assimilation. Furthermore, SMOS sea ice ~~thicknesses have~~ thickness has been assimilated into the Massachusetts Institute of Technology general circulation model (MITgcm) with a localized Singular Evolutive Interpolated Kalman (LSEIK) filter (Yang et al. 2014). They show that the assimilation leads to improved ice thickness forecasts, as well as better sea ice concentration forecasts.

To improve the accuracy of the sea ice thickness assimilation it is possible to consider other sea ice parameters, such as the sea ice fractional coverage or ice/snow surface ~~temperatures~~temperature. A common approach to do that is to assimilate brightness temperatures rather than a ready-to-use high-level satellite product. The advantage is the availability of a wide range of consistent input data, whereas independent sea ice thickness retrievals ~~rely~~ force radiative transfer models with input that relies on assumptions, parameterizations and ~~independet~~ independent auxiliary data, such as climatologies or secondary reanalysis products. However, the question remains which radiative transfer model suits best to be used as a forward operator in a brightness temperature assimilation scheme for thin sea ice ~~thicknesses~~thickness. So far, simulated brightness temperatures have been validated for idealized typical Arctic conditions (e.g. Maaß et al. (2013), Tian-Kunze et al. (2014)), but have never been compared to L-Band remote sensing observations on a large scale.

In this study, we investigate the Arctic-wide performance of the radiative transfer models of Kaleschke et al. (2010) and Maaß et al. (2013) to account for diverse atmospheric and oceanic conditions and to identify the most important input parameters for a sea ice thickness application. In preparation for a brightness temperature assimilation, we concentrate on the input data of the global ocean reanalysis product ORAP5 (Ocean ReAnalysis Pilot 5) produced by the ECMWF (Zuo et al., 2015). We evaluate which radiative transfer model to use for assimilating sea ice thickness into the ORAP5 ~~reanalyses~~ reanalysis by comparing simulated and observed brightness temperatures from the radiative transfer models with ORAP5 input data and SMOS observations, respectively.

2 Data and Methods

~~Both~~

2.1 Radiative transfer models

For our analysis we selected the radiative transfer models ~~provide brightness temperatures as a function of temperature, snow- and sea ice thickness, incidence angle and the permittivity (Fig. ??). The latter is calculated with the snow, sea ice and sea water temperatures (as well as the snow/sea ice interface temperature), the bulk sea ice and water salinities and the snow and sea ice thicknesses. The sea ice salinity is estimated with the empirical approach of Ryvlin (1974) making the ice salinity a function of the sea surface salinity, the sea ice thickness , the salinity ration of the bulk ice salinity at the end of the sea ice growing season and the growth rate coefficient. The latter two are taken from Kovacs (1996) who derived a value of 0.175 for the ice salinity ration from observational data in the Arctic and 0.5 for the growth rate coefficient, as also suggested by Ryvlin (1974). To obtain the ice/snowinterface we calculate the thermal conductivity of ice with the snow surface temperature and ice salinity (Untersteiner, 1964). Using this, we are able to determine the bulk sea ice temperature for our sea ice slab by assuming the heat fluxes are in equilibrium (Maykut and Untersteiner, 1971). We calculate the brine salinity with a polynomial approximation that uses bulk sea ice temperature (Vant et al., 1978; Leppäranta and Manninen, 1988) and the pure ice density~~ of Kaleschke et al. (2010) and Maaß et al. (2013) to simulate brightness temperatures above sea water and ice at 1.4 GHz. The two models have been chosen because the model of Kaleschke et al. (2010) is a rather simple single-layer model that has been successfully applied for operational sea ice thickness retrieval (Kaleschke et al., 2012), whereas the model of Maaß et al. (2013) consists of multiple layers and is yet only used for sensitivity studies above snow. Both models provide brightness temperatures as a function of bulk ice temperature (Pounder, 1965). As the polynomial coefficients for the brine salinity calculation are only provided for 1 and 2 GHz, we linearly interpolate between these two frequencies to determine the coefficients for 1.4 GHz. By taking the ice and brine density, as well as the bulk ice temperature, we are able to calculate brine volume fraction using equations valid for ice temperatures below -2°C from Cox and Weeks (1983) and above -2°C from Leppäranta and Manninen (1988). Finally, the permittivityof sea ice is derived by an empirical relationship to the brine volume fraction (Vant et al., 1978) (for a summary of references see table **??**)the considered layers' temperature, thickness and permittivity.

Simplified schematic illustration for the determination of auxiliary parameters provided to the radiative transfer models utilized in this study. The studies for the methods are listed in Table **??**. A listing of all input data and the most important parameters is given in Table **??**. Boxes with white background indicate input data from OPAP5 reanalyses.

In order to represent sea ice brightness temperature measurements in partially covered data points over the open ocean, the models linearly include sea ice fractional coverage in the calculations for each grid cell. Additionally, both models consider the subpixel-scale heterogeneity of sea ice thicknesses with a statistical ice thickness distribution. We calculate the brightness temperatures for ten linearly divided sea ice thickness bins with a maximum of 2 meter thickness. Then, we translate the mean sea ice thickness from the input data to a sea ice thickness distribution derived by observational data (As used in Algorithm II* by Tian-Kunze et al. (2014)). The final brightness temperature is the average of the ten respective bins weighted by the sea ice thickness distribution.

Applied methods to obtain auxiliary parameters for brightness temperatures calculations above sea ice and snow. The numbers in the first row refer to the numbers in Fig.**??**. No. Parameter References 1 Bulk ice salinity Ryvlin (1974) 2 Ice thermal conductivity Untersteiner (1964) 3 Snow/Ice interface and bulk temperatures Maykut and Untersteiner (1971) 4 Brine salinity Vant et al. (1978); Leppäranta and Manninen (1988) 5 Brine volume fraction Cox and Weeks (1983) 6 Snow permittivity Tiuri (1984) 7 Sea ice permittivity Vant et al. (1978) 8 Brightness temperatures Kaleschke et al. (2010), Maaß et al. (2013)

Sea water emissivity calculations are based on Fresnel equations with the descriptions of sea water after Ulaby et al. (1981) with permittivities obtained by Klein and Swift (1977). Wind induced sea surface roughness influences are assumed to be small and will be neglected (Dinnat et al., 2003). To account for corrections of the galactic background radiation and atmospheric deviations a simplified atmospheric model (Peng et al., 2013) is taken forced by climatological data from 65 years of NCEP data (Kalnay and Kanamitsu, 1996). The cosmic contribution to the overall brightness temperatures is set to 2.7 Kelvin. In these simulations, we restrict the brightness temperature calculation to nadir incidence angle. The freezing temperature of sea water is set to -1.8°C.

*The single-layer model*Individual modifications of the coherent The radiative transfer model of Kaleschke et al. (2010) as used in Tian-Kunze et al. (2014) include the assumption describes the microwave emission of a dielectric slab of a single layer of sea ice with a semi- infinite semi-infinite layer of air on top and a semi-infinite layer of ocean water below (the model is further referred to as KA2010). The model considers a single layer of bare sea ice. To obtain an incoherent solution

, Kaleschke et al. (2010) extends the model with a sea ice roughness approximationTo obtain a solution converging to the brightness temperature of open water for close to zero ice thickness, Kaleschke et al. (2010) introduces a parameterization for the sea ice thickness variability used for semi-incoherent averaging. As long as the root mean square thickness variations of the illuminated footprint are much larger than the electromagnetic wavelength used in the model, it is possible to average the emissivity over a variety range of sea ice thicknesses which assumes assuming that all coherent propagation effects are averaged out. The model does not add a separate snow layeron top of the sea ice (thermal conductivity set to climatological value of $k_{snow} = 0.31$ (Yu and Rothrock, 1996)). In that setup, include a dynamic snow layer; however, the presence of snow influences the brightness temperatures by a temperature insulation of sea ice from the atmosphere. As snow covers the ice it dampens the influence of atmospheric temperature changes to the ice. The effect appears to be significant and can be considered within the sea ice /snow interface temperature. An additional thermodynamic model as used in Tian-Kunze et al. (2014) becomes redundant since we use auxiliary data for surface temperatures. simulated brightness temperatures through the effect of thermal insulation of the upper sea ice layer.

*The multi-layer model*The incoherent model used in

The radiative transfer model from Maaß et al. (2013) is based on radiative transfer equations and describes the emitted radiation from a stratified bare soil upwelling brightness temperature at h and v polarisation from snow and sea ice represented by plane-parallel layers without surface roughness (referred as MA2013). The core equations are taken from Burke et al. (1979), but it has been substantially modified to suit the needs for sea ice model extends the radiative transfer model of Burke et al. (1979) with assumptions of snow and sea ice permittivities. In our simulations the MA2013 model consists of three layers of sea ice and one layer of snow on top of the ice. All ice layers have the same properties except for the sea ice thickness that is simply divided by the number of layers considered and the ice ice temperature that linearly changes between the lowest layer bordering the ocean and the upper layer facing the atmosphere. The snow is assumed to be dry and has a snow density of $\rho_{snow} = 330\ [kg/m^3]$ that accounts for the climatological average value for Arctic average snow density over sea ice in March (Warren G. et al., 1999). In contrast to the previous model model of Kaleschke et al. (2010), the snow layer does not only affect the temperature of the underlying sea ice, but also the radiation incidence angle, potentially leading to propagation effects. Snow changes the refraction index and thus the reflectivity between the air-snow and snow-ice boundaries. By changing the optical properties of the air-ice boundary and the temperature of sea ice, snow has a passive effect on the brightness temperature (Schwank Mike et al., 2015).

. As an addition to the model described in Maaß et al. (2013) we added the ability to take multiple reflections and refractions within the sea ice into account. Thus, the radiative beams are followed on their way through the layers of snow and take into account multiple reflections within sea ice and added up when they leave the medium in upper direction towards the atmosphere. Reflected beams are removed after 15 interface passings when they are not able to leave the ice-snow medium on the short term. At this point, the intensity of the radiative beams are negligible and we are able to cap the computational effort for the calculation . instead of only considering first order reflectivity.

Both models consider the sea ice thickness subpixel-scale heterogeneity of open ocean and sea ice with a statistical ice thickness distribution obtained by observations (As used in Algorithm II* by Tian-Kunze et al. (2014)). We calculate the brightness temperatures for ten linearly divided sea ice thickness bins with a maximum of 1 meter thickness in order to represent typical first year sea ice. Then, the brightness temperature is the average of the ten respective bins weighted by the sea ice thickness distribution.

Sea water emissivity calculations are based on Fresnel equations with the descriptions of sea water after Ulaby et al. (1981) with permittivities obtained by Klein and Swift (1977). Wind induced sea surface roughness influences are assumed to be small and will be neglected (Dinnat et al., 2003). To correct for galactic background radiation and atmospheric deviations an atmospheric model (Peng et al., 2013) is taken, forced by climatological mean from 65 years of NCEP data (Kalnay and Kanamitsu, 1996). The cosmic contribution to the overall brightness temperatures is set to 2.7 K. In these simulations, we restrict the brightness temperature calculation to nadir incidence angle. The freezing temperature of sea water is set to -1.8°C.

2.2 The ORAP5 reanalysesreanalysis

The radiative transfer models are forced using data from the Ocean ReAnalysis Pilot 5 (ORAP5) project, which is provided by the European Centre of Medium range Weather Forecast (ECMWF) (Tietsche et al., 2014). The sea ice and snow thicknessesthickness and snow depth, the surface and sea water temperaturestemperature, the sea ice fractional coverage and the sea surface salinity are taken from ORAP5 data(Table ??). The . The reanalysis has been produced using the NEMO global ocean model version 3.4has been utilized to , which was run on the DRAKKER DRAKKAR ORCA025.L75 configuration for 34 years, covering the years from 1979 to 2013. The configuration uses a tripolar mesh grid with poles located in Greenland and Central Asia in the northern hemisphere, as well as a pole in the Antarctic in the southern hemisphere. The spatial resolution ranges from 1/4 degree at the equator to a couple of kilometers in the polar regions with 75 vertical levels in the ocean. The atmospheric forcing fields are derived from the ERA-Interim reanalyses reanalysis (Dee et al., 2011).

The dynamic-thermodynamic Louvain-la-Neuve Sea Ice Model second generation (LIM2) has been coupled to the NEMO ocean model (Bouillon et al., 2009). Sea ice is represented with a two-dimensional viscous-plastic rheology that interacts with the atmosphere and the ocean. A simple three-layer model (one for snow and two layers for ice) is used at which to determine sensible heat storage and vertical heat conductionare determined. Vertical heat fluxes are calculated based on the thermodynamic energy balance according to Semtner (1976)Semtner (1976). The sea ice thickness is determined by the surface balance of radiative, turbulent and heat fluxes and the conductive heat balance between the bottom part of the sea ice and the ocean. Snow is accumulated by solid precipitation in case sea ice is present. If the surface temperature of the snow-ice system exceeds freezing temperature the surface temperature keeps unchanged at the freezing point and the remaining energy is put into melting of snow and afterwards sea ice. The albedo is a function of the snow and ice thicknessesthickness, the state of the surface and the cloudiness. Sea ice coverage is derived by the surface energy balance over open water, the contribution of closing leads and the Operational SST and Sea Ice Analysis (OSTIA) system, which assimilates sea ice concentration from the Satellite Application Facility on Ocean and Sea Ice (OSI-SAF) dataset produced by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).

Table 1. ~~Input parameters with uncertainties provided for~~ Uncertainties of the ~~calculation scheme. The letters refer to Fig. ??. As~~ ORAS5 reanalysis and monthly variations of the ORAP5 ~~reanalyses product does not provide uncertainties, we use~~ reanalysis for the ~~uncertainties of~~ radiative transfer model input parameters expressed as the ~~follow-on product ORAS5 reanalyses~~99% quantile.

~~Letter~~ ~~A~~ No.	~~Input parameter~~ ~~Snow density~~ Model parameter	~~Value~~ ~~330 kgm^{-3}~~Nov 2012	ORAS5 uncertainty ~~unchanged~~ Mar 2013	~~U~~
~~B~~ height1	~~Thermal conductivity of snow 0.31~~ Sea ice thickness [~~$Wm^{-1}K^{-1}$~~m]	~~unchanged~~ 0.24	~~Yu and Rothrock (1996) C~~ 0.17	~~Ice~~
~~D~~ 2	~~Growth rate coefficient~~ Sea ice concentration [%]	~~0.5~~ 4.4	~~unchanged~~ 8.1	~~R~~
~~E~~ 3	Sea ice ~~thickness variable 0.3~~ temperature [~~m~~K]	~~ORAP5 F~~ 0.31	~~Snow thickness~~ 0.87	~~v~~
~~G~~ 4	~~Sea surface salinity variable 0.42~~ Snow depth [~~$g * kg^{-1}$~~m]	~~ORAP5 H~~ 0.03	~~Snow/ice surface temperature~~ 0.03	~~v~~
~~I~~ 5	Sea surface ~~temperature variable 0.54~~ salinity [~~K~~$g * kg^{-1}$]	~~ORAP5 H~~ 0.38	~~Sea ice concentration~~ 0.32	~~v~~

2.3 ~~The ORAP5 reanalyses~~

This study focuses on the winter season in 2012/2013, more precisely on November 2012 and March 2013. The period has been chosen due the availability of the reanalysis dataset ORAP5 and SMOS measurements (v. 5.05). As a pilot-project with the goal to deliver ocean reanalysis with highest quality standards the dataset is not yet operational and therefore further processed. The link between brightness temperatures and sea ice thicknesses is established in low temperatures (Kaleschke et al., 2010) due to the ice permittivity's dependency on brine volume fraction, which in turn depends on ice temperature and salinity (Pounder, 1965; Cox and The connection between the ice permittivity on the brine volume fraction is the basis of the sea ice thickness retrieval and will be of the sea ice thickness assimilation. November and March are the first and the last month in which temperatures are below freezing in the winter season (Vikhamar-Schuler et al., 2016) and are therefore chosen.

As the ORAP5 ~~reanalyses~~ reanalysis does not provide uncertainties on ~~their~~ its own, we use the uncertainties ~~for the abovementioned parameters~~ from the follow-on product ORAS5 ~~reanalyses~~ reanalysis (Zuo et al., in preparation). The uncertainty ~~value~~ values listed in table ~~?? is the~~ 1 represent the deviation of 99% ~~quantile of all uncertainties~~ of all values in an area north of 50°N ~~and is meant to represent the highest deviation from the reanalyses to reality. The assumption made here is that the uncertanties of the reanalyses product are much lower than the monthly variation of the physical properties. Therefore the majority of brightness temperature difference will be due to the performance of the radiative transfer model. Still, the output of the radiative transfer models do fully depend on the input values provided by the reanalyses product and will be thus influenced by its uncertainties.~~ over first year ice (1 m and below). We use the 99% quantile to exclude outliers and find a representative value for the majority of grid cells. The same statistical quantity is used for the seasonal variation of changing physical property between the beginning and the end of the month for November and March.

~~This study focuses on the winter season in 2012/2013, more precisely on November in 2012 and March 2013. The period has been chosen due the availability of the reanalyses dataset ORAP5 and SMOS measurements (v. 5.05). As a pilot-project with the goal to deliver ocean reanalyses with highest quality standards the dataset is not yet operational and therefore further processed. The second limiting factor is a reasonable time-frame to describe brightness temperature changes with varying sea~~

~~ice thicknesses. In the melting season, when melt ponds form on sea ice and temperatures begin to rise, SMOS brightness temperatures over sea ice are impossible to connect to a specific sea ice property (Kaleschke et al., 2010). Thus, November and March are the first and the last month, respectively, with full monthly data coverage from SMOS and therefore chosen.~~

2.3 SMOS brightness temperatures

SMOS is equipped with a passive microwave 2D-interferometer called MIRAS (Microwave Imaging Radiometer with Aperture Synthesis) operating in L-Band at 1.4 GHz (~21 cm). It measures brightness temperatures in full-polarization up to 65° incidence angle every 1.2 seconds (Kerr et al., 2001). The hexagonal snapshots have a swath-width of around 1200 km, which allows a global coverage. Each point on earth is observed at least once every three days with a daily coverage in the polar regions due to SMOS quasi-circular sun-synchronous orbit at 758 km height.

SMOS snapshots ~~are~~ can be influenced by Radio frequency interference (RFI) rooting from radar, TV and radio transmission (Mecklenburg et al., 2012). To account for the most critical disturbances, a RFI filter has been utilized. Brightness temperatures above 300 K identify a snapshot to be RFI-contaminated and ~~be further~~ are ignored for the brightness temperature product. ~~The threshold of 300 K is chosen as values~~ Values higher than that are not expected to be seen in the Arctic ~~or Antarctic.~~ between November and March as the physical maximum of a surface with temperature at the freezing point would be 273.15 K if the emissivity was 1.

The brightness temperature product ~~consists of~~ is provided at vertical and horizontal polarization~~, which are averaged up~~ . Although these measurements vary with incidence angles the intensity, defined as the average of horizontally and vertically polarised brightness temperatures, remains almost constant in the range of 0 to 40 ~~° incidence angle when they are taken within 2.5 seconds time-interval (Kaleschke et al., 2012). These brightness temperatures are said to represent L-Band measurements at nadir as brightness temperature changes that are connected to the varying incidence angles are expected to cancel out each other when both polarisations are considered~~degrees over sea ice. By averaging over this incidence angle range we obtain more brightness temperature data per grid point per day reducing considerably the uncertainty. The averaged product is available on a daily basis up to 85°N latitude. The data is collected for an entire day and is averaged for each grid point to provide a L3B daily mean brightness temperature product. Finally, the data is geolocated on a NSIDC polar-stereographic projection that provides grid cells with the same areal extent of 12.5 km horizontal resolution.

3 ~~Sea water correction~~

2.1 Brightness temperatures bias correction above sea water

To investigate the quality of the radiative transfer models for ~~partially covered~~ sea ice areas in the ORAP5 setup we want to keep the brightness temperature difference above sea water as small as possible. Thus, we first check the representation of ~~emissivities~~ brightness temperatures over open ocean of the models. ~~As mentioned before, both~~ Both models use the same equations to calculate the emissivity of water areas based on Klein and Swift (1977) and will thus produce the same brightness temperatures using same input data. Therefore we here only show the correction for MA2013. In any case, L-Band brightness temperature variations in open Arctic Arctic open waters are low compared to sea ice and should fairly match between observed SMOS the difference between SMOS measurements and simulated brightness temperatures from the radiative transfer models should be less than 2 K assuming temperatures around freezing point and 30 psu salinity (Berger et al., 2002).

We simulate brightness temperatures in all open water areas north of 50° latitude. As a first step, we project the ORAP5 reanalyses reanalysis on the polar-stereographic grid SMOS is using. Afterwards, we obtain a monthly average by calculating brightness temperatures for each day of the month using daily input data. Then, we average all brightness temperatures corresponding to a single day to a monthly value. We find an average bias of 3.093 Kelvin 3.1 K between MA2013 and the SMOS observations in November and March (Fig. 1). To identify the open water areas, we exclude all data points with potential sea ice on it a fractional sea ice coverage above zero in the ORAP5 reanalysis and also exclude all data points flagged as land. Furthermore, brightness temperatures of more than 120 Kelvins are most unlikely to account for Arctic open water areas K are considered as outliers and are excluded as well. Finally, a total of 99085 data points show an average open water brightness temperature of SMOS $\overline{TB}_{SMOS} = 100.68K$ $\overline{TB}_{SMOS} = 100.7K$, whereas the models have an average of $\overline{TB}_{model} = 97.58K$. $\overline{TB}_{model} = 97.6K$.

To correct for the bias of open water areas we add the difference of 3.093 Kelvin 3.1 K to the overall brightness temperature of sea water. Subsequent Subsequently, results of the radiative transfer models show the main accumulation of data points at around 100 Kelvins K and a second, weaker one beginning at 105, each one with a tail towards higher brightness temperatures of SMOS. The first tail at 100 Kelvin can be explained by will be due to the gradual transition between land and water areas. As the SMOS land sea product only distinguishes between fully covered land and water points, it does not represent partially covered measurements of pixels containing land and water. The region of higher TBs are located in the Baltic Sea. In that area, lower sea surface salinities salinity and higher water temperatures temperature compared to the rest of the Arctic waters leads to higher brightness temperatures. The water bias correction However, this is not a general statement about the quality of the brightness temperatures above Arctic sea water but a correction only for this analysis. The correction is used in all following simulations using the radiative transfer models.

3 Brightness temperature comparison

2.1 Sea ice growth model

To obtain a reference point for Arctic sea ice thickness growth for the radiative transfer model sensitivity study in 3.1, we utilize an empirical sea ice growth model (Lebedev, 1938). The sea ice thickness increase is parameterized by $d = 1.33\Theta^{0.58}$ [cm] with the freezing days $\Theta = \int(T_f - T_a)dt$ as a function of the freezing point of sea water $T_f \approx -1.9°C$ (Maykut, 1986) and the surface air temperature T_a [in °C]. The sea ice growth model has been used in various previous studies (e.g. Yu and Lindsay, 2003) and will provide an initial estimate of the sea ice thickness growth over a certain time period.

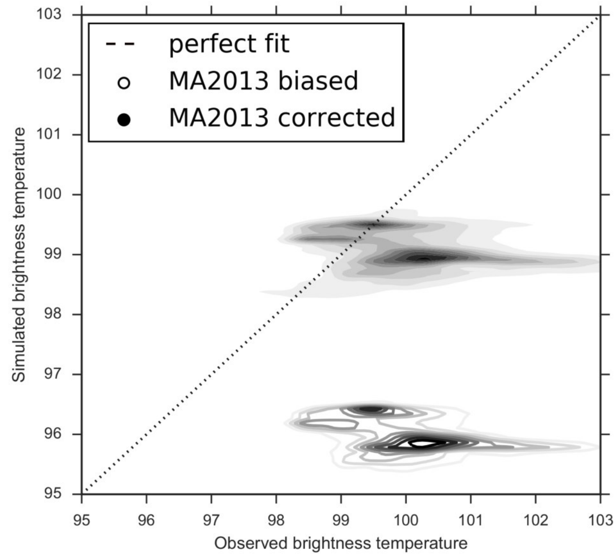

Figure 1. ~~Open~~ Sea water brightness temperature comparison between SMOS and MA2013. ~~A~~ Contour lines (MA2013 biased) represent a direct comparison between simulated and measured brightness temperature above open sea water~~bias~~. Filled contours (MA2013 corrected) represent the same comparison but with a correction ~~is applied to all~~ for simulated brightness temperatures of 3.1 K.

3 Results

3.1 Brightness temperature comparison

Brightness temperatures simulated with MA2013 are generally higher than brightness temperatures of KA2010 by up to around 15 Kelvins (Fig. 2). ~~Largest~~ The largest differences are located in the outer sea ice zones with the highest magnitude where sea ice ~~concentrations are~~ concentration is close to 100%, and an increase of sea ice thickness with time is expected, such as in the East Siberian Sea or the Canadian Arctic Archipelago in November, or the Sea of Okhotsk in March. For a first evaluation of the brightness temperature models, the two extreme cases of open water and 100% multi-year thick sea ice can be considered. Since we already treated the lower boundary of open ocean brightness temperatures with a water bias correction as indicated above, we now concentrate on the upper boundary of a saturated signal over thick sea ice areas. We find higher simulated brightness temperatures in the central ~~parts~~ part of the Arctic ~~simulated~~ by MA2013. The ~~saturated~~ value in MA2013 ~~appears to be~~ saturates around ∼~~250 Kelvin~~ 255 K whereas KA2010 ~~only shows~~ shows a maximum ∼240 ~~Kelvins. The differences between both models are lowest in the areas where multi-year sea ice is expected close to Greenland (NSDIC). There is no indication~~ K. There are no indications for seasonal changes between brightness temperatures from November and March expect the increased area covered by sea ice. The variability in ~~November shows a slightly larger spatial~~ March shows a larger variation of brightness temperature ~~due to more new sea ice formation~~difference close to the sea ice edge.

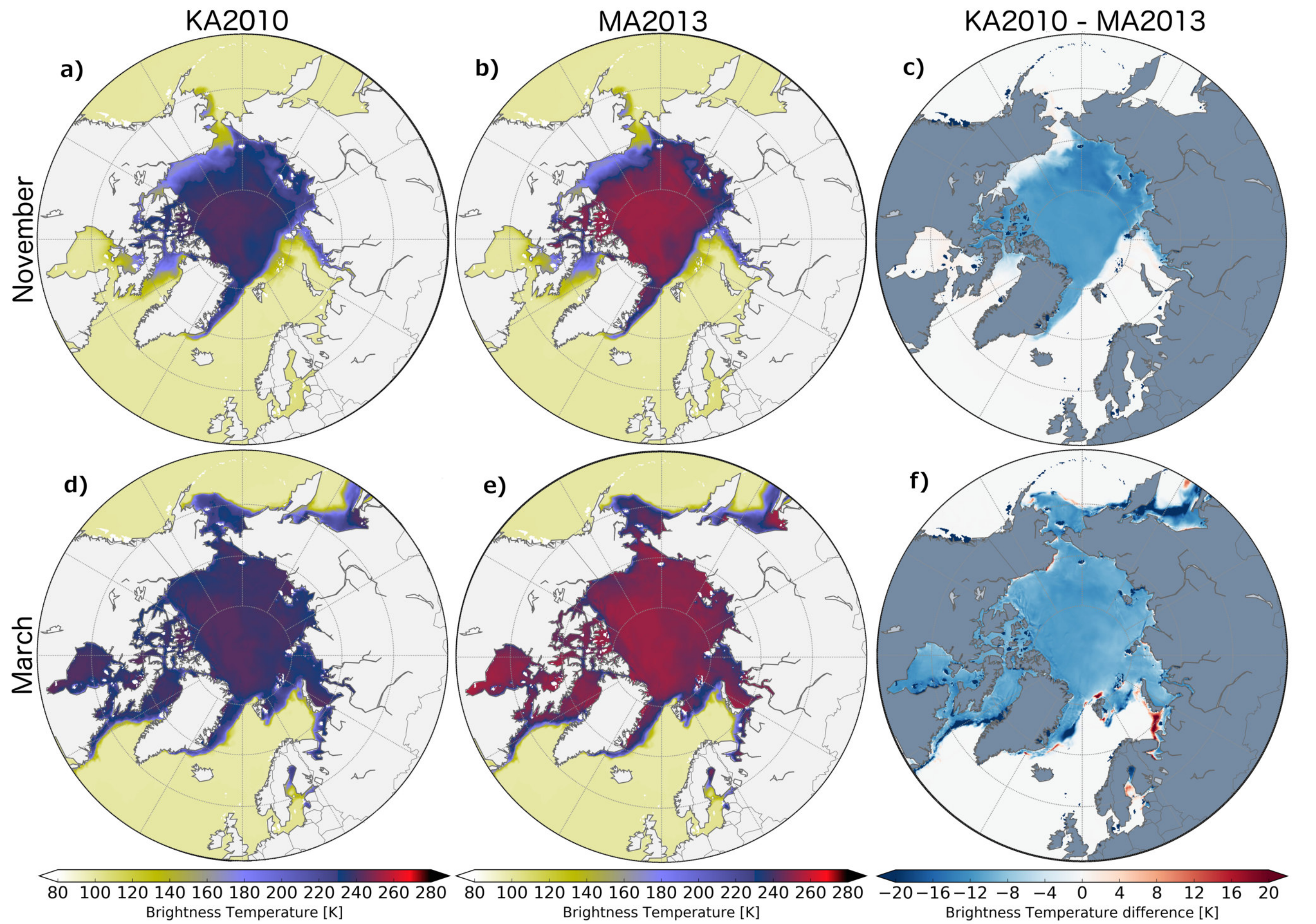

Figure 2. Monthly brightness temperatures simulated by KA2010 (left column) and MA2013 (center column). (**a-c**) shows the November 2012 brightness temperature distribution based on ORAP5 ~~reanalyses~~ reanalysis input data with a comparison plot of both models at (**c**). (**d-f**) is equal, but for March 2013.

Brightness temperatures measured by SMOS appear to be in between the simulated ones of KA2010 and MA2013 influenced by strong spatial differences (Fig. 3). In November 2012, both models show higher brightness temperatures in the East Siberian Sea and the Canadian Arctic Archipelago. Lower brightness temperatures are located in the Canadian Basin and the Chukchi Sea with extension to the Bering Street. A different picture is shown in the central Arctic at grid points with more than 80% sea ice concentration coverage, where both models simulate brightness ~~with deviations to~~ temperatures with deviations of opposite directions. ~~The~~ In is area, the model of KA2010 shows lower (~~-2.84 ± 5.58~~-2.37 ± 7.28K) and MA2013 higher (~~9.17 ± 5.69~~9.38 ± 7.46K) brightness temperatures compared to SMOS observations ~~.~~ in November 2012. The same is true for March 2013, although ~~that~~ KA2010 (~~0.39 ± 4.04~~0.30 ± 7.13K) shows a stronger agreement in the central Arctic than MA2013 (~~10.78 ± 4.31~~10.84 ± 7.06K). ~~In November 2012, brightness~~ Brightness temperature deviations between KA2010 and the SMOS measurements ~~are of smaller spatial extent than in MA2013 and~~ show a higher variability between positive and negative differences. MA2013 appears to be positively biased not only in November 2012, but also in March 2013. The simulations exceed SMOS brightness temperatures almost everywhere in the Arctic with deviations up to 20 ~~Kelvins~~ K in the Labrador Sea and Sea of Okhotsk. ~~There are no large differences observed in open water areas, except places close to coastal areas that confirms the quality of the water bias correction .~~

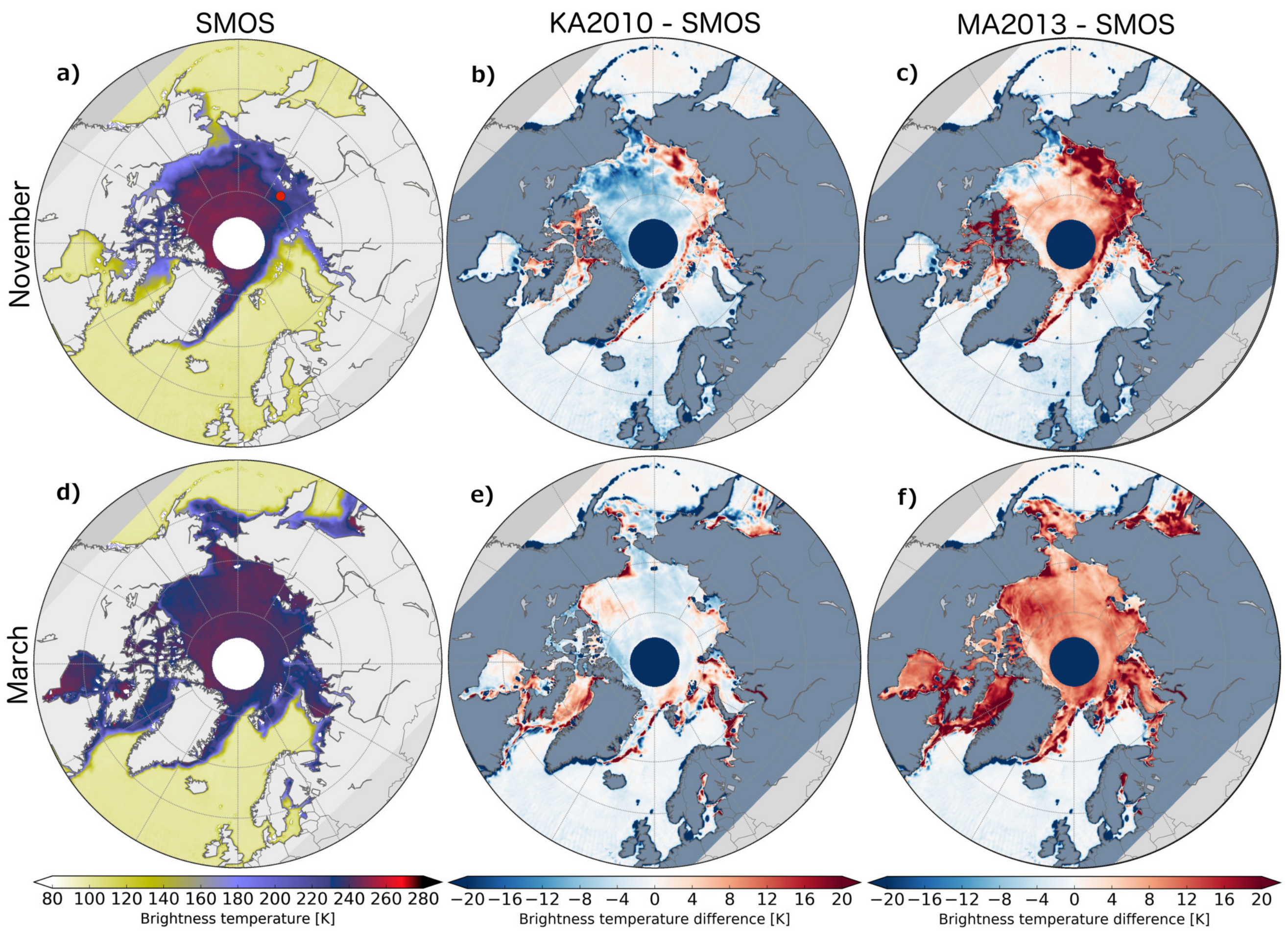

Figure 3. SMOS brightness temperatures (**a,d**) compared with simulated brightness temperatures using KA2010 (**b,e**) and MA2013 (**c,f**) in November 2012 (**a-c**) and March 2013 (**d-f**). The red dot in (**a**) indicates the position of the investigated grid cell in the Laptev Sea.

A ~~general~~ comparison between all simulated and modeled brightness temperatures in the Arctic ~~show that most~~ shows that 92% data points are located ~~in the open water region at around~~ at 105~~Kelvins and more central areas at around~~ ±3 K and 240~~Kelvins~~ ±7 K (Fig. 4). The latter is associated with thicker sea ice related to saturated brightness temperatures at 1.4 GHz. ~~In November, simulated brightness temperature appear to correspond~~ Simulated brightness temperature shows a high correlation of the distribution state of $r = 0.98$ or $r = 0.97$ with SMOS measurements. KA2010 ~~shows lower brightness temperatures of around~~ brightness temperatures are on average 2 ~~Kelvins throughout the whole range~~K lower than SMOS in November, whereas MA2013 simulates larger brightness temperatures in thick ice regions in March and November. Furthermore, as already seen in figure 3, MA2013 overestimates brightness temperatures above ~~$\sim$~~$\sim$190 Kelvins also in March. The ~~individual brightness temperature spread is biggest~~ difference between simulated and observed brightness temperatures is largest in between the main clusters~~(not shown here)~~, although most points appear to concentrate around the 1:1 line. ~~The correlations of all distributions state $r = 0.98$ is astonishing, although the reason might be the overwhelming majority of points located at the open water and saturated fix points.~~

~~Figure ?? shows the cumulative probability function over all simulated and observed brightness temperatures over sea ice in the Arctic. In November approximately 40% of brightness temperatures are below 220 Kelvin, when it is only $\sim$ 15% in March. First, the brightness temperature distribution increases linearly until the aforementioned threshold and then quickly saturates around 240 Kelvins. A Kolmogorov-Smirnov-Test ($\alpha = 0.1$) of the cumulative probability function over all data points of the Arctic rejects all simulated brightness temperature distributions except for KA2010 in March 2013.~~

~~Cumulative probability density function of Arctic-wide brightness temperatures over sea ice in November 2012 (left) and March 2013 (right).~~

~~4 Radiative transfer model sensitivity study~~

3.1 Radiative transfer model sensitivity study

In order to identify the most important input variables for the radiative transfer models, we evaluate the sensitivity of the models to certain changes of sea ice, snow and sea water parameters. We keep all but one parameter fixed at a monthly value and calculate the brightness temperatures for the minimum and the maximum simulated value within the month for one physical parameter. That will give us two different brightness temperatures, one for the minimum, one for the maximum, of which the difference is the range of brightness temperature change related to one of the parameters that can be expected. Varying all input parameters provided by the ORAP5 ~~reanalyses~~ reanalysis we quantify the impact of certain physical parameters on our brightness temperatures at a specific place over the time span of one month.

The most important input parameters for brightness temperature calculations with the radiative transfer models are the sea ice fractional coverage, sea ice thickness and sea ice temperature (Fig. 5, accounting for 92% grid points in March and November). For both seasons, the sea ice temperature has the largest impact on the brightness temperatures in the central Arctic with the largest spatial extent in MA2013. ~~The sea ice temperature becomes even more important in~~ In March when the ~~overall~~ Arctic sea ice extent ~~is greatest throughout the year in up to~~ reaches its maximum, the ice temperature is the most important parameter in about 25% of the area of the Arctic. Closer to the outer sea ice regions, the sea ice fractional coverage is most influential for the largest part of the Arctic sea ice (around 60% of the total sea ice area). During the sea ice growth season in November, the leading impact of sea ice fraction extends all the way to the coastal areas in the East Siberian Sea, whereas the Canadian Basin is dominated by sea ice thickness growth. In any case, the sea ice thickness is most important ~~in a large area~~ close to the sea

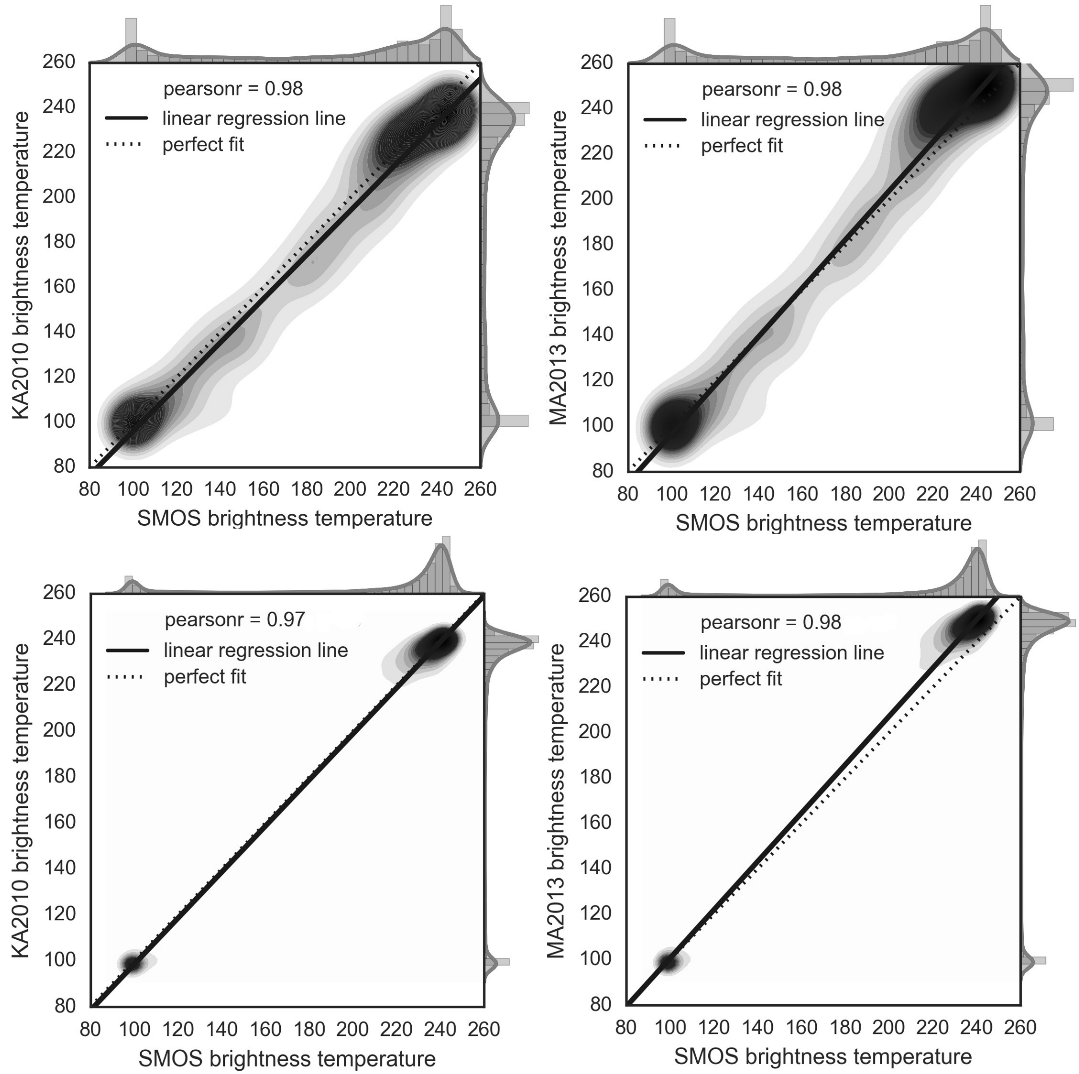

Figure 4. Brightness temperature comparison between simulated and observed brightness temperatures in November 2012 (top) and March 2013 (bottom) for KA2010 (left) and MA2013 (right). The pearson correlation r between simulated and observed brightness temperatures over sea ice for MA2013 and KA2010, respectively is stated in the legend.

ice edge (25% of the area in November). ~~This is partially true when sea ice thicknesses are~~ The impact is lower when the sea ice thickness is predominantly thicker than half a meter and ~~exceed~~ exceeds SMOS sensitivity (5% in March). However, the effect of sea ice concentration and thickness is similar in both models. In the very outer marginal sea ice zone it appears that sea surface temperature dominates (7%). The sea surface salinity only contributes in very small areas in the Fram-Strait where ~~sea surface temperatures and salinities~~ the sea surface temperature and salinity are higher (<1%).

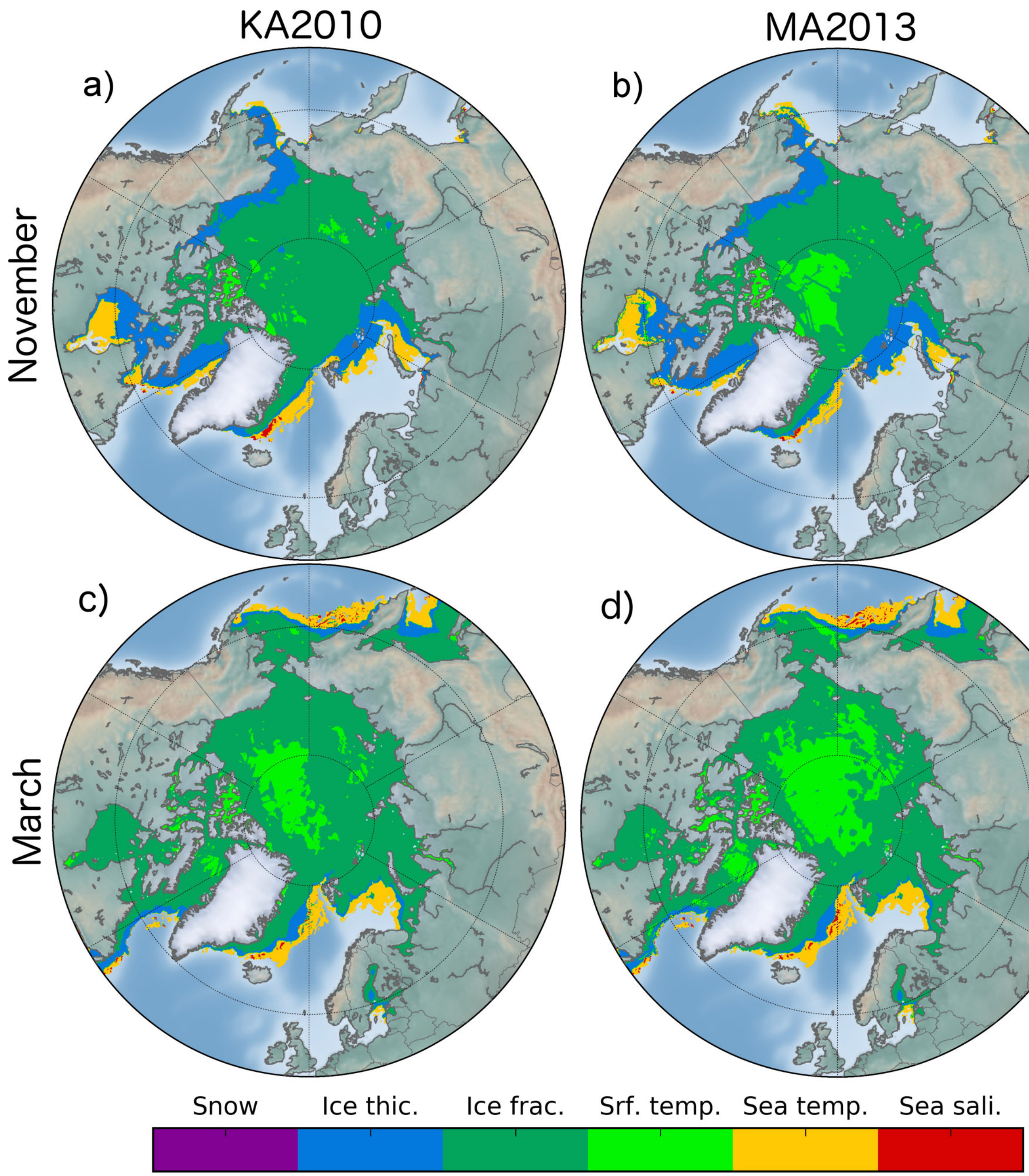

Figure 5. Most influencial physical variables from ORAP5 on the brightness temperature gradient. Monthly values are shown for November 2012 (**a-b**) and March 2013 (**c-d**) for KA2010 (**a-c**) and MA2012 (**b-d**).

~~Freeze-up event in October to November 2012 that took place in the Laptev Sea (77.5 N, 137.5 E). Brightness temperature time-series of from KA2010, MA2013 and SMOS measurements (top) and sea ice thickness and concentration time-series of ORAP5, ASI and Lebedev retrieval model data (bottom).~~

An overview of the influence of single parameters on the brightness temperature simulation using KA2010 and MA2013 is given in table **??**. One parameter varies over a range of values, whereas all other parameters are fixed to a default value similar to the method used in Fig. 5. The range of values is set to be the 99% quantile of its largest simulated change within the month of November. This calculation is performed twice, once for a thin sea ice scenario and once for a thick sea ice scenario. As expected it is shown that the sea ice concentration and sea ice thickness has the greatest influence on the brightness temperature calculation on a range from 0 - 100% and 0-0.77m. The brightness temperature difference is up to 149 Kelvin in the case of thicker sea ice and the MA2013 model. The effect is less strong in KA2010 but still dominating. However, the sea ice temperature, snow thickness and sea ice salinity are also highly important. A change of snow thickness from no snow to a 40 cm snow layer will change the brightness temperature around 28 Kelvin in both models for thin and thick sea ice. Third most important is the sea ice temperature accounting for brightness temperature changes up to 24 Kelvin in a range from -35 to -5 °C, slightly more in the KA2010 model. The sea ice salinity accounts for around 20 Kelvin in case of thin sea ice and 12 or 6 Kelvin for KA2010 or MA2013, respectively, in case of thick sea ice. The influence of sea ice salinity appears to be more sensitive to sea ice thickness in MA2013 than in KA2010, as we see a larger change between thin and thick sea ice. For the sea surface salinity and the snow density, we are do not observe a great influence. These above examined values may alter significantely by changing the default value, but will give us good insight into the relation of physical parameters to simulated brightness temperatures.

An overview of the influence of single parameters on the brightness temperature simulations using KA2010 and MA2013 is given in table **??**. One parameter varies over a range of values, whereas all other parameters are fixed to a default value similar to the method used in Fig. 5. The range of values is set to be the 99% quantile of its largest simulated change of the value within the month of November. At that time, changes are assumed to be greatest as it is in the middle of the sea ice growth season. This calculation is performed twice, once for thin sea ice (10cm) and once for a thick sea ice (50cm) except in case of varying sea ice thickness. As expected it is shown that the sea ice concentration and sea ice thickness has the largest influence on the brightness temperature calculation on a range from 0 - 100% and 0 - 0.77 m, respectively. In case of thin sea ice the effect on brightness temperatures appears to be even more sensitive for sea ice thickness changes up to 159 K in the MA2013 model. However, a monthly change of sea ice temperature, snow thickness and sea ice salinity also has a noticable impact on the brightness temperature calculation. The sea ice temperature is most important with changes up to 14 Kelvin in the KA2010 model. The snow thickness and sea ice salinity are roughly half of that. By comparing the impact with the thick sea ice scenario the influence of the sea ice temperature, snow thickness and sea ice salinity decreases, whereas sea ice concentration becomes more dominant. This is especially true for the model of MA2013, in which the sea ice concentration and the sea ice thickness influence is greatest, most pronounced in the thin sea ice scenario. These above examined values may alter significantely by changing the default value, which is here chosen to represent typical Arctic and Antarctic first year ice. Still, it will give us insight into the relation of physical parameters to simulated brightness temperatures.

For a more The propagating errors from ORAP5 uncertainties to the brightness temperature simulations are shown in table 2. Similar to the method used in fig. 5 one parameter varies over a range of values whereas all other parameters are fixed to a default value. The range of values is set to be the ORAS5 monthly uncertainty of November (Table 1). At that time, the sea ice

Table 2. Changes of simulated brightness temperatures in KA2010 and MA2013 related to different alternating physical parameters. The table shows two range is based on the ORAS5 uncertainties of November (Tab. 1). Two cases of thin sea ice (10 cm) and thicker sea ice (50 cm) are shown.

No.	Parameter	ΔTB at 10cm in [K] KA2010	ΔTB at 10cm in [K] MA2013	ΔTB at 50 cm in [K] KA2010	ΔTB at 50 cm in [K] MA2013	Default value	Range
1	Sea ice thickness	132 120	159 152	132 120	159 152	0.1 [m]/ 0.5 [m]	0 - 0.77 0.24 [m m]
2	Sea ice concentration	67 4	129 6	142 8	173 8	100 [%]	0 95.6 - 100 [% %]
3	Sea ice temperature	14 0	10 0	6 0	4 1	-5 [°C]	-24 -6 - -5 [°C]
4	Snow thickness depth	7 3	3 4	0 1	1	Ice thickness * 0.1	0 - 0.1 0.03 [m m]
5	Sea surface salinity	0	1 0	0	0	30 [$g*kg^{-1}$]	28 29.8 - 32 30.2 [$g*kg^{-1}$ $g*kg^{-1}$]
6	Sea ice salinity	5 2	9 7	5 15	4 12	8 [$g*kg^{-1}$]	4 - 12 [$g*kg^{-1}$ $g*kg^{-1}$]

thickness uncertainty is higher than in March as it is in the middle of the sea ice growth season. This calculation is performed twice, once for thin sea ice (10 cm) and once for a thick sea ice (50 cm) (except in case of varying sea ice thickness). For both sea ice thickness values, the ORAP5 sea ice thickness uncertainty of 24 cm dominates the simulated brightness temperature signal with a value up to 152 K in MA2013. The influence of all other physical properties do not exceed more than 8 K except the sea ice salinity with values up to 15 Kelvin. The effect of the sea ice temperature and sea surface salinity vanishes in this case of thin sea ice.

For a more detailed analysis on the contribution of sea ice thickness and concentration to the modelled brightness temperatures, a sample freeze-up situation is investigated at a point located in the Laptev Sea (77.5°N, 137.5°E) from October to November 2012 (Fig. 6). The observational sea ice concentration product ASI (ARTIST Sea Ice algorithm, (Kaleschke et al., 2001; Spreen et al., 2008) shows a rapid freeze-up to 80% sea ice coverage in just a few days. The brightness temperatures of SMOS measurements and the KA2010 and MA2013 models properly agree show high agreement with some exceptions on the first days of the freezing period that starts around the 25. October. The simulated brightness temperatures appear to be underestimated underestimate the SMOS measurements at the beginning of the season which leads to a more linear brightness temperature increase rather than a logarithmic shape as observed from the SMOS measurements. However, the simulated sea ice concentration of ORAP5 appears to be is lower than the the observed ASI sea ice concentration and needs almost two weeks to catch up to the same coverage as ASI. The sea ice thickness on the other hand shows a fast thickening to more than half a meter even before the main freeze-up event takes place. The sea ice growth model of Lebedev (1938) accumulates sea ice as a function of the temperature difference between the surface air temperatures temperature and freezing point of water, as well as the number of freezing days below zero degrees. In contrast to the sea ice thickness of ORAP5, Lebedevs' parameterization shows a gradual increase of ice thickness throughout the freeze-up event. Following, we observe an underestimation of sea ice concentration and an overestimation of sea ice thicknesses, although the brightness temperatures between observational and simulated data fits decently well thickness in the reanalysis over a range of two weeks, whereas the SMOS brightness temperature only deviate more than 20 K for 5 days.

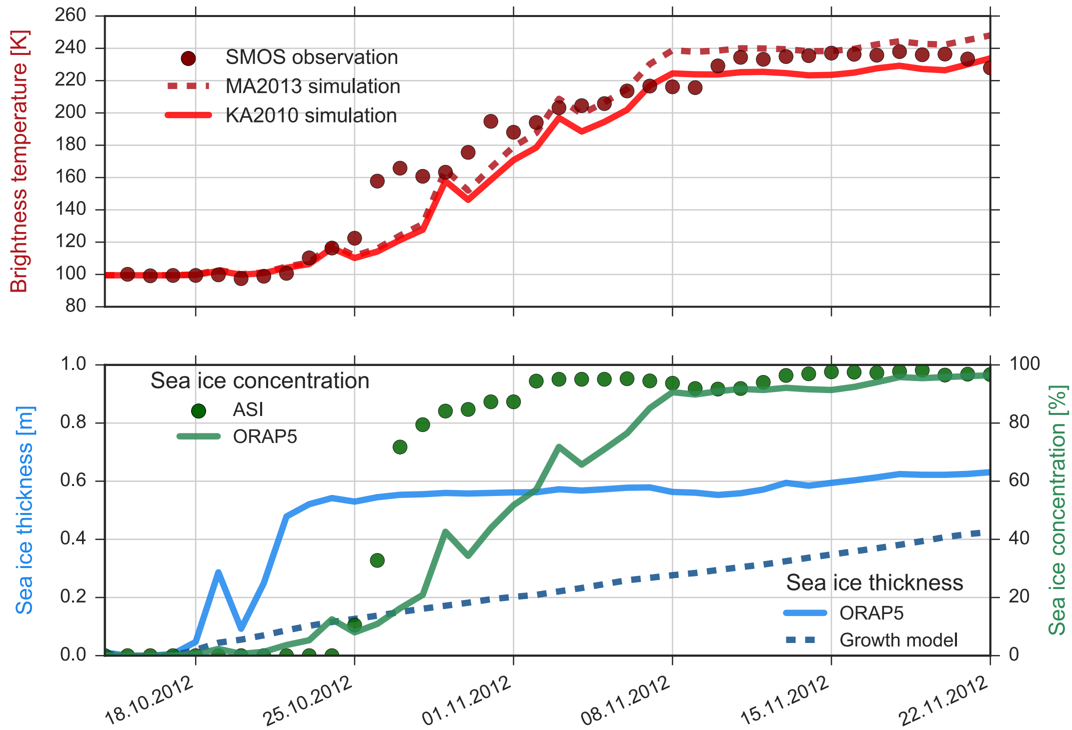

Figure 6. Freeze-up event in October to November 2012 that took place in the Laptev Sea (77.5 N, 137.5 E). Brightness temperature time-series of from KA2010, MA2013 and SMOS measurements (top) and sea ice thickness and concentration time-series of ORAP5, ASI and Lebedev retrieval model data (bottom).

4 Discussion

~~The simulated brightness temperatures from two incoherent~~ Our results indicate that brightness temperature differences up to around 15 K, and even higher differences at the ice edge, can be due to the usage of different radiative transfer models ~~with~~ (Fig. 2). Even though both models tend to have the same signatures, KA2010 shows lower brightness temperatures than the MA2013 in the whole Arctic. This was expected as the MA2013 model is able to take multiple sea ice layers into account, as well as the radiometric effect of snow on top of sea ice, whereas KA2010 only indirectly includes the effect of snow with the representation of the thermodynamic insulation effect. However, compared with SMOS brightness temperatures, it appears that MA2013 driven with the ORAP5 ~~input data generally match the SMOS observations in an overall Arctic-wide comparison.~~ output overestimates brightness temperatures in many parts of the Arctic, most pronouncedly in March in the central Arctic region. This area is mostly covered by thick sea ice. We cannot assimilate SMOS data here because microwave radiation does not contain information on the thickness of thicker sea ice. In contrast, KA2010 shows good agreement in the central Arctic area. For brightness temperature assimilation purposes that would be clearly beneficial as the main assimilation should take place in regions with thin sea ice rather than in the central Arctic. Therefore, a more comprehensive representation of sea ice with radiative transfer equations using multiple layers does not necessarily need to be an advantage for brightness temperature assimilation.

The analysis shows spatial differences between SMOS and simulated brightness temperatures throughout the Arctic with largest differences in the outer Arctic regions for November 2012 and March 2013. However, the sign of the deviation changes according to the region. In the East Siberian Sea both models simulate higher brightness temperatures compared with SMOS, whereas lower values are shown in the Canadian Basin. In the latter the fractional sea ice coverage increased from almost open water up to an average value of 60% in November, whereas the coverage in the East Siberian Sea ~~kept~~ stayed more or less constant at 100% (not shown here). ~~The Canadian Basin experienced an initial freeze-up from open ocean to a thin sea ice layer. As microwave radiation in L-Band is most sensitive to changing sea ice with thicknesses of only a few centimeters (e.g. Kaleschke et al. (2012)),~~ To estimate the sea ice thickness from brightness temperature measurements, the sea ice concentration ~~changes become~~ becomes more important the thicker the sea ice gets~~and brightness temperatures approach saturation.~~ .The reasons are: 1) The brightness temperature difference between ice and water is higher for thicker ice, thus a changing ice concentration changes the mixture's brightness temperature more than for thinner ice. 2) Due to the lower sensitivity of the L-band signal to ice thickness for thicker ice, the brightness temperature difference induced by changing ice concentration leads to a higher ice thickness difference for thicker ice than for thinner ice. (e.g. Kaleschke et al. (2012)). That makes it necessary to use a high-precision auxiliary sea ice concentration product to account for brightness temperature changes due to alteration in sea ice concentration. ~~As~~

Here, we provide sea ice fractional coverage from our ~~reanalyses~~ reanalysis to the radiative transfer models ~~, we are~~ and are thus able to reduce the uncertainty of sea ice fraction changes compared to studies with an assumption of a constant 100% sea ice concentration coverage ~~(Tian-Kunze et al., 2014)~~(Table 2)(Tian-Kunze et al. (2014)). However, ~~changes still remain essential . An uncertainty of 10%~~ the quality of the ice concentration data is essential for the quality of L-band brightness temperature assimilations. At a sea ice thickness of around 50cm, an uncertainty of 5% fractional sea ice coverage accounts for a difference of ~~15 Kelvin at sea ice thicknesses of around 40 cm(Kaleschke et al., 2010). In the same scenario,~~ 8 K (Kaleschke et al., 2010), which in turn can result in a sea ice thickness uncertainty of more than 10 cm. In occasional events, the deviation of sea ice concentration from the reanalysis data to the here investigated ASI sea ice concentration can be even higher with differences up to 40% (Fig. 6). The largest error is due to the sea ice thickness with an estimated uncertainty of 24 cm for ORAP5 in November 2012corresponding to a brightness temperature ~~change of 15 Kelvins may stand for a~~ difference of 120 K and 152 K for thin ice (below 24 cm) in KA2010 or MA2013, respectively. This uncertainty is more than 10 times higher than all other uncertainties in case of typical first year sea ice represented by the default values in table 2 except for sea ice salinity which is a function of sea ice thickness ~~uncertainty of more than 20 cm~~and sea surface salinity (Ryvlin, 1974). This is benefical for assimilation purposes as 93% in MA2013 or 90% in KA2010 of all brightness temperature deviations between SMOS and the radiative transfer models are rooted in the sea ice thickness (compare table 2).

In order to assimilate thin sea ice ~~thicknesses~~ thickness it is crucial to understand the impact of all physical parameters on the brightness temperature simulations. Kaleschke et al. (2012) found sea ice concentration and thickness changes in thin sea ice areas are the most important variables for L-Band brightness temperatures. We here support this evidence as our most dominating dependencies for brightness temperature simulations are found to be the same throughout the Arctic (Fig. 5). Over thick sea ice in the central Arctic we find the sea ice/snow surface temperature to be the most influential parameter. Since sea ice concentration is close to 100% and sea ice ~~thicknesses are above~~ thickness is above the L-Band ~~sensitivies~~sensitivity, brightness temperature changes are due to the impact of snow ~~thickness~~ depth and sea ice/snow temperature changes that ~~comes~~ come with it. ~~But also in~~ In thin sea ice regions, variations of sea ice temperature, snow ~~thickness~~ depth and sea surface salinity can have an accumulated influence of up to more than 25 ~~Kelvin (Table ??).~~ K (not shown).

~~This is evidence to have even more accurate information about the sea ice state.~~

Our results also show a significant influence of sea ~~ice/snow and sea surface temperatures~~ surface temperature and salinity in areas of thin sea ice close to the ice edge. This is explained by a fractional sea ice coverage of less than 10%, where brightness temperature variations are dominated by changing open water emissivities. We point out that sea surface temperature and ~~salinities~~ salinity get more important in regions with lower sea ice coverage. Therefore, in case partially ~~covered sea ice concentrations~~ ice-covered areas are taken into account we caution that a climatology of sea ~~ice/snow surface temperatures or sea surface salinities~~ surface temperature or salinity might not be sufficient enough to picture the transition between open water towards the sea ice edge. This is especially true for the declining sea ice observed in the recent years as the sea ice edge is likely to be located at a different location than in the previous years.

~~Our results indicate that brightness temperature differences up to around 15 Kelvin can be due to the usage of different radiative transfer models (Fig. 2). Even though both models tend to have the same signatures, KA2010 shows lower brightness temperatures than the MA2013 in the whole Arctic. This was expected as the MA2013 model is able to take multiple sea ice layers into account, as well as the radiometric effect of snow on top of sea ice, whereas KA2010 only indirectly includes the effect of snow with the representation of the thermodynamic insulation effect. Compared with SMOS brightness temperatures, it appears that MA2013 overestimates brightness temperatures in many parts of the Arctic, most pronouncedly in March in the central Arctic region. For a brightness temperature assimilation this would be rather detrimental, as we only expect benefits from SMOS-based ice thickness assimilation thin sea ice regions because microwave radiation is not able to distinguish between thicker sea ice. In contrast, KA2010 shows good agreement in the central Arctic area. For brightness temperature assimilation purposes that would be clearly beneficial as the main assimilation should take place in regions with thin sea ice rather than in the central Arctic. Additionally, MA2013 shows a rapid brightness temperature rise in the transition from open water towards the very first centimeters of sea ice (Kaleschke et al. (2010), Maaß et al. (2013)). Therefore, a more comprehensive representation of sea ice with radiative transfer equations using a multiple layers does not necessarily need to be an advantage for brightness temperature assimilation.~~

~~The majority of all data points accumulates in the vicinity of the perfect fit, although in March,~~ A comparison of SMOS and simulated brightness temperatures showed a Pearson correlation of 0.97- 0.98. However, most of the data points are located at brightness temperatures for either the saturated case at 240/~~250 Kelvin~~ 255 K for KA2010/MA2013 or open water areas at around 100 K (Fig. 4~~and Fig. ??). The~~), especially in March. The reason is that 92% of all simulated data points over sea ice are larger than 220 K. The overall performance in terms of the range of simulated brightness temperatures over sea ice is explained by the Kolmogorov-Smirnov test ($\alpha = 0.1$). The test ~~accepts only~~ determines the accordance of two different datasets without making any assumption about the distribution of the data (Sachs and Hedderich, 2006). In the K-S-test, $1-\alpha$ is the probability that two data sets originate from the same distribution, or in other words, α is the confidence to accept a hypothesis. Here, the test only accepts the brightness temperature distribution from March 2013 of KA2010. ~~The reason is because 92% of all simulated data points are higher than 220 Kelvin.~~ Therefore, it is most important for the model to agree with the saturated case in order to determine reasonable areas for brightness temperature assimilation ~~.~~ in that KA2010 in March agrees most. We specifically concentrate on the saturated case, as it is next to water the only reliable reference point we can address for a quality assessment of the models. Thus, based on ORAP5 ~~reanalyses~~ reanalysis input data and electromagnetic formulations used here, we suggest to use the KA2010 radiative transfer model for brightness temperature assimilation. However, for the remaining 8% of all simulated data points with intermediate sea ice thickness and concentration we are unable to find a favourable radiative transfer model as the results of the models are superimposed by the sea ice thickness uncertainty. Note, that this is no statement about the quality of the radiation model in general, than rather a suggestion for the specific ~~specification utilized in this study in terms of applied~~ assumptions and characteristics of the LIM2 sea ice ~~model~~models that were used in this study.

Although the statistical representation of brightness temperatures is well captured, we find large discrepancies in times of rapid sea ice changes (Fig. 6). For an example case, ORAP5 appears to have difficulties to simulate freeze-up events~~by both,~~ , in which we see an overestimation of sea ice thickness and an underestimation of sea ice concentration. The assimilation of OSI-SAF sea ice concentration into ORAP5 pushes the sea ice concentration into the right direction, but appears to be too slow to picture changes in a short period of time. A smaller fractional sea ice concentration and an overestimation of sea ice thickness then ~~leads~~ lead to simulated brightness temperatures that fit with observed SMOS brightness temperatures, even though both parameters are ~~clearly wrong~~ divergent at this time. In this case, a SMOS brightness temperature assimilation in ORAP5 may not bring much benefit as we cannot distinguish between the influence of sea ice concentration and thickness. An auxiliary sea ice concentration data product is needed to correct brightness temperature calculations for possible differences in sea ice cover. We therefore suggest a combined assimilation of brightness temperatures covering a broad spectral range from 1.4 to 37 GHz yielding information on both, sea ice thickness and concentration.

All brightness temperature calculations rely on the quality of the ORAP5 data as the results are highly influenced by uncertainties of the input parameters. A comprehensive sea ice concentration and sea ice thickness comparison between ORAP5 and observational products was made by Tietsche et al. (2015) who found an agreement of sea ice concentration in ORAP5 and OSTIA in the order of magnitude of 5% root mean square deviation. ~~As aforementioned, this uncertainty~~ Assuming this is an optimistic estimation as OSTIA sea ice concentration is assimilated into ORAP5, the uncertainty still accounts for 7-8 ~~Kelvin~~K, explaining up to more than 10 cm ice thickness difference in case of thicker sea ice and is therefore still critical. They point out that the representation of sea ice thickness in thin sea ice regions ~~need~~ needs further improvements, especially in the vicinity of the ice edge. However, the initial freeze-up sea ice thickness in the LIM2 sea ice model is set to 0.5 m leading to an overestimation of sea ice ~~thicknesses~~ thickness in newly formed sea ice areas. Sea ice of half a meter thickness is mostly already at the maximum thickness for a brightness temperature assimilation and will lead to essential brightness temperature differences between modeled and observational data. This is a strong argument for a brightness temperature assimilation, as it might help to correct the overestimation of ORAP5 sea ice ~~thicknesses~~ thickness in freeze-up areas.

5 Summary and outlook

The radiative transfer models from Kaleschke et al. (2010) (denoted as KA2010) and Maaß et al. (2013) (MA2013) are taken as a forward operator to simulate brightness temperatures at 1.4 GHz in the winter season 2012/2013 and to identify the feasibility of the models for a brightness temperature assimilation in the global ocean reanalyses reanalysis product ORAP5. Using ORAP5 input data, we compared modeled brightness temperatures with SMOS observations in November 2012 and March 2013 accounting for the start and the end of the winter season, respectively.

The results of this study indicate that both models are able to simulate Arctic-wide monthly brightness temperatures. We are able to observe a similar increase of simulated and observed brightness temperatures from thin to thicker sea ice areas. Although both models show a decent fit in November, the model of Maaß et al. (2013) tends to overestimate brightness temperatures in the saturated case of thick sea ice in March with the configurations applied here. A Kolmogorov-Smirnov test thus only accepts the brightness temperature distribution of KA2010 in March by taking the SMOS observation as the reference probability distribution. All other, especially the results of MA2013 in March, are rejected. Therefore, we suggest to use the model of KA2010 for a brightness temperature assimilation into the ORAP5 reanalyses project. reanalysis project. This suggestion is primarily based on a comparison between SMOS and simulated brightness temperatures over thick sea ice and open water and does not make a statement about the ability of the model to reproduce brightness temperatures in thin sea ice conditions.

The most important parameters for the brightness temperature calculations over thin sea ice are identified to be the sea ice thickness and sea ice coverage. This result supports the findings of other studies (e.g. Kaleschke et al. (2012)). In thicker sea ice areas the dominant parameter is the sea surface temperature since the sea ice fractional coverage is close to 100% and sea ice thickness changes do not affect the measurements at 1.4 GHz. The influence of the sea ice temperature, snow thickness depth and sea ice salinity increases in thinner sea ice areas but will still be less than the sea ice thickness and concentration. However, the smaller the sea ice fractional coverage, the more important are the sea surface temperature and salinity. This becomes relevant at sea ice concentrations concentration below 15%, usually in small regions at the very outer sea ice edge.

The brightness temperature assimilation is expected to result in a more accurate sea ice thicknesses thickness analysis than a direct assimilation of the physical parameter as the climate model provides a series of input variables to the forward operator. These variables do not need to be replaced by climatologies, parameterizations or assumptions that may inflict the results of our sea ice thickness retrieval. However, even though the sea ice thickness and concentration in ORAP5 are well constrained by observations (Tietsche et al., 2015), both show difficulties to represent a rapid freeze-up event with an underestimation of sea ice concentration and an overestimation of sea ice thickness. That reveals the challenge to use brightness temperatures to correct for the right physical parameter and magnitude. We recommend to combine the brightness temperature assimilation for sea ice thickness with the assimilation of an independent auxiliary observational sea ice concentration product or the simultaneous assimilation of measurements taken at higher microwave frequencies, e.g. up to 37 GHz.

The assimilation of SMOS brightness temperatures appears to be a great chance for a better representation of sea ice thicknesses thickness in the ORAP5 reanalysesreanalysis. Substantial differences between observational and simulated brightness temperatures are found to be largest in regions with of thin sea ice, in which SMOS uncertainties of the sea ice thickness retrievals are lowest (Kaleschke et al., 2010). That reveals the possibility to retrieve and correct sea ice ~~thicknesses~~ thickness in future investigations. However, to what magnitude these results translate to other ~~reanalyses~~ reanalysis products or climate forecasts has to be investigated.

6 Data availability

L3B Brightness temperatures are provided by the CliSAP-Integrated Climate Data Center (ICDC) on http://icdc.cen.uni-hamburg.de/1/daten/cryosphere/l3b-smos-tb.html (Tian-Kunze et al., 2012). The ~~reanalyses~~ reanalysis data of ORAP5 was kindly provided by ~~the~~ ECMWF and is freely available on http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHYS_001_017 (Zuo et al., 2015). The ORAS5 uncertainties will be soon available at http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets.

Acknowledgements. We thank Steffen Tietsche for the provision of ORAP5 ~~reanalyses~~ reanalysis data, Andreas Wernecke who helped to implement the cosmic and galactic background radiation representation. We thank the "Science Snack" team for fruitful discussions.

References

Albergel, C., Rosnay, P. D., Gruhier, C., Muñoz-sabater, J., Hasenauer, S., Isaksen, L., Kerr, Y., and Wagner, W.: Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations, Remote Sensing of Environment, 2011.

Berger, M., Camps, a., Font, J., Kerr, Y., Miller, J., Johannessen, J., Boutin, J., Drinkwater, M. R., Skou, N., Floury, N., Rast, M., Rebhan, H., and Attema, E.: Measuring ocean salinity with ESA's SMOS mission - Advancing the science, Esa Bulletin-European Space Agency, pp. 113–121, 2002.

Bouillon, S., Morales Maqueda, M. a., Legat, V., and Fichefet, T.: An elastic-viscous-plastic sea ice model formulated on Arakawa B and C grids, Ocean Modelling, 27, 174–184, doi:10.1016/j.ocemod.2009.01.004, 2009.

Burke, W. J., Schmugge, T., and Paris, J. F.: Comparison of 2.8- and 21-cm microwave radiometer observations over soils with emission model calculations, Journal of Geophysical Research, 84, 287–294, doi:10.1029/JC084iC01p00287, 1979.

Cox, G. F. and Weeks, W.: Salinity variations in sea ice, Journal of Glaciology, 13, 109–120, 1973.

Cox, G. F. and Weeks, W. F.: Equations for determining the gas and brine volumes in sea ice samples, Tech. rep., 1983.

Dee, D. P., Uppala, S. M., Simmons, a. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. a., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, a. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, a. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, a. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, doi:10.1002/qj.828, http://doi.wiley.com/10.1002/qj.828, 2011.

Dinnat, E. P., Boutin, J., Caudal, G., and Etcheto, J.: Issues concerning the sea emissivity modeling at L band for retrieving surface salinity, Radio Science, 38, n/a–n/a, doi:10.1029/2002RS002637, http://doi.wiley.com/10.1029/2002RS002637, 2003.

Gabarro, C., Turiel, A., Elosegui, P., A. Pla-Resina, J., and Portabelle, M.: Measuring sea ice concentration in the Arctic Ocean using SMOS, The Cyrosphere, doi:10.5194/tc-2016-175, 2016.

Kaleschke, L., Heygster, G., and Lüpkes, C.: SSM/I sea ice remote sensing for mesoscale ocean-atmosphere interaction analysis: Ice and icebergs, … of Remote Sensing, 2001.

Kaleschke, L., Maaß, N., Haas, C., Hendricks, S., Heygster, G., and Tonboe, R. T.: A sea-ice thickness retrieval model for 1.4 GHz radiometry and application to airborne measurements over low salinity sea-ice, Cryosphere, 4, 583–592, doi:10.5194/tc-4-583-2010, 2010.

Kaleschke, L., Tian-Kunze, X., Maaß, N., Mäkynen, M., and Drusch, M.: Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophysical Research Letters, 39, n/a–n/a, doi:10.1029/2012GL050916, 2012.

Kaleschke, L., Tian-Kunze, X., Maaß, N., Beitsch, A., Wernecke, A., Miernecki, M., Müller, G., Fock, B. H., Gierisch, A. M., Schlünzen, K. H., Pohlmann, T., Dobrynin, M., Hendricks, S., Asseng, J., Gerdes, R., Jochmann, P., Reimer, N., Holfort, J., Melsheimer, C., Heygster, G., Spreen, G., Gerland, S., King, J., Skou, N., Søbjærg, S. S., Haas, C., Richter, F., and Casal, T.: SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment, doi:10.1016/j.rse.2016.03.009, 2016.

Kalnay, E. and Kanamitsu, M.: The NCEP/NCAR 40-Year Reanalysis project, Bulletin of the …, 1996.

Kerr, Y. H., Waldteufel, P., Wigneron, J. P., Martinuzzi, J. M., Font, J., and Berger, M.: Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission, IEEE Transactions on Geoscience and Remote Sensing, 39, 1729–1735, doi:10.1109/36.942551, 2001.

Kerr, Y. H., Member, S., Waldteufel, P., Richaume, P., Wigneron, J. P., Member, S., Ferrazzoli, P., Member, S., Mahmoodi, A., Bitar, A. A., Cabot, F., Gruhier, C., Juglea, S. E., Leroux, D., Mialon, A., and Delwart, S.: The SMOS Soil Moisture Retrieval Algorithm, 50, 1384–1403, 2012.

Klein, L. and Swift, C.: An improved model for the dielectric constant of sea water at microwave frequencies, Oceanic Engineering, IEEE Journal of, 2, 104–111, doi:10.1109/joe.1977.1145319, 1977.

Kovacs, A.: Part I . Bulk Salinity Versus Ice Floe Thickness, 1996.

Kwok, R. and Cunningham, G. F.: ICESat over Arctic sea ice: Estimation of snow depth and ice thickness, Journal of Geophysical Research: Oceans, 113, 1–17, doi:10.1029/2008JC004753, 2008.

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S., and Davidson, M.: CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophysical Research Letters, 40, 732–737, doi:10.1002/grl.50193, 2013.

Lebedev: Rost l'da v arkticheskikh rekakh i moriakh v zavisimosti ot otritsatel'nykh temperatur vozdukha, 5-6 edn., 1938.

Leppäranta, M. and Manninen, T.: The brine and gas content of sea ice with attention to low salinities and high temperatures, 1988.

Lindsay, R. and Schweiger, a.: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, The Cryosphere, 9, 269–283, doi:10.5194/tc-9-269-2015, http://www.the-cryosphere.net/9/269/2015/, 2015.

Maaß, N., Kaleschke, L., Tian-Kunze, X., and Drusch, M.: Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data, The Cryosphere, 7, 1971–1989, doi:10.5194/tc-7-1971-2013, 2013.

Maaß, N., Kaleschke, L., Tian-Kunze, X., and Tonboe, R. T.: Snow thickness retrieval from L-band brightness temperatures: a model comparison, Annals of Glaciology, 56, 9–17, doi:10.3189/2015AoG69A886, 2015.

Maykut, G.: The surface heat and mass balance, 1986.

Maykut, G. and Untersteiner, N.: Some results from a time-dependent thermodynamic model of sea ice, Journal of Geophysical Research, http://onlinelibrary.wiley.com/doi/10.1029/JC076i006p01550/full, 1971.

Mecklenburg, S., Drusch, M., Y.H. Kerr, Font, J., Martin-Neira, M., Delwart, S., Buenadicha, G., Reul, N., Daganzo-Eusebio, E., and Oliva, R.: ESA ' s Soil Moisture and Ocean Salinity Mission - Mission overview and first results, Geophysical Research Abstracts, 13, 3628–3628, 2012.

Meier, W.: Actic sea ice in tranformation: A review of recent observed changes and impacts on biology, Reviews of Geophysics, 53, 1–33, doi:10.1002/2013RG000431.Received, 2015.

Menashi, J. D., St Germain, K. M., Swift, C., Comiso, J. C., and Lohanick, A.: Low-frequency passive-microwave observations of sea ice in the Weddell Sea., Journal of Geophysical Research: Oceans, 98, 22 569 – 22 577, 1993.

Peng, G., Meier, W. N., Scott, D. J., and Savoie, M. H.: A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring, Earth System Science Data, 5, 311–318, doi:10.5194/essd-5-311-2013, 2013.

Pounder, E.: The Physics of Ice, Pergamon Press, the Commonwealth and International Library, Geophysics Devision, Oxford, p. 151, 1965.

Reul, N., Fournier, S., Boutin, J., Hernandez, O., Maes, C., Chapron, B., Alory, G., Quilfen, Y., Tenerelli, J., Morisset, S., Kerr, Y., Mecklenburg, S., and Delwart, S.: Sea Surface Salinity Observations from Space with the SMOS Satellite: A New Means to Monitor the Marine Branch of the Water Cycle, Surveys in Geophysics, 35, 681–722, doi:10.1007/s10712-013-9244-0, 2014.

Ricker, R., Hendricks, S., Helm, V., Skourup, H., and Davidson, M.: Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation, Cryosphere, 8, 1607–1622, doi:10.5194/tc-8-1607-2014, 2014.

Ryvlin, A. I.: Method of forecasting flexural strength of an ice cover, Probl. Arct. Antarct, 45, 79–86, 1974.

Sachs, L. and Hedderich, J.: Angewandte Statistik, Springer, p. 338, 2006.

Schwank Mike, Mätzler, C., Wiesmann, A., Wegmüller, U., Pulliainen, J., Lemmetyinen, J., Rautiainen, K., Derksen, C., Toose, P., and Drusch, M.: Snow Density and Ground Permittivity Retrieved from L-Band Radiometry: A Synthetic Analysis, IEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2015.

Semtner, A.: A model for the thermodynamic growth of sea ice in numerical investigations of climate, Journal of Physical Oceanography, 1976.

Spreen, G., Kaleschke, L., and Heygster, G.: Sea ice remote sensing using AMSR-E 89-GHz channels, Journal of Geophysical Research, 113, C02S03, doi:10.1029/2005JC003384, 2008.

Stark, J. D., Ridley, J., Martin, M., and Hines, A.: Sea ice concentration and motion assimilation in a sea ice-ocean model, Journal of Geophysical Research: Oceans, 113, 1–19, doi:10.1029/2007JC004224, 2008.

Tian-Kunze, X., Kaleschke, L., and Maass, N.: SMOS Daily Polar Gridded Brightness Temperatures, [2012-2013], icdc.cen.uni-hamburg.de, 2012.

Tian-Kunze, X., Kaleschke, L., Maaß, N., Mäkynen, M., Serra, N., Drusch, M., and Krumpen, T.: SMOS-derived thin sea ice thickness: algorithm baseline, product specifications and initial verification, The Cryosphere, 8, 997–1018, doi:10.5194/tc-8-997-2014, http://www.the-cryosphere.net/8/997/2014/, 2014.

Tietsche, S., Balmaseda, M. A., Zuo, H., and Mogensen, K.: Arctic sea ice in the ECMWF MyOcean2 ocean reanalysis ORAP5, p. 33, http://old.ecmwf.int/publications/library/ecpublications/{_}pdf/tm/701-800/tm737.pdf, 2014.

Tietsche, S., Balmaseda, M. a., Zuo, H., and Mogensen, K.: Arctic sea ice in the global eddy-permitting ocean reanalysis ORAP5, Climate Dynamics, doi:10.1007/s00382-015-2673-3, http://link.springer.com/10.1007/s00382-015-2673-3, 2015.

Tilling, R. L., Ridout, a., and Shepherd, a.: Near Real Time Arctic sea ice thickness and volume from CryoSat-2, The Cryosphere Discussions, pp. 1–15, doi:10.5194/tc-2016-21, 2016.

Tiuri, M. E.: The Complex Dielectric Constant of Snow at Microwave, IEEE Journal of Oceanic Engineering, 9, 377–382, 1984.

Ulaby, F. T., Moore, R. K., and Fung, A. K.: Microwave remote sensing.Active and passive., Kansas Univ.; Lawrence, KS, United States, 1981.

Untersteiner, N.: Calculationsof TemperatureRegime and Heat Budget of Sea Ice in ,the Central Arctic, 69, 4755–4766, 1964.

Vant, M. R., Ramseier, R. O., and Makios, M.: The complex-dielectric constant of sea ice at frequencies in the range 0.1-40 GHz., Journal of Applied Physics, 49, 1264–1280, 1978.

Vikhamar-Schuler, D., Isaksen, K., Haugen, J. E., Tommervik, H., Luks, B., Vikhamar-Schuler, T., and Bjerke, J. W.: Changes in Winter Warming Events in the Nordic Arctic Region, Journal of Climate, 29, 6223 – 6244, doi:10.1175/JCLI-D-15-0763.14, 2016.

Warren G., S., Rigor G., I., Untersteiner, N., Radionov F., V., Bryazgin N., N., Aleksandrov I., Y., and Colony, R.: Snow Depth on Arctic Sea Ice, Journal of Climate, 1999.

Xie, J., Counillon, F., Bertino, L., Tian-kunze, X., and Kaleschke, L.: Benefits of assimilating thin sea ice thickness from SMOS into the TOPAZ system, The Cryosphere, 10, 2745–2761, doi:10.5194/tc-10-2745-2016, 2016.

Yu, Y. and Lindsay, R. W.: Comparison of thin ice thickness distributions derived from RADARSAT Geophysical Processor System and advanced very high resolution radiometer data sets, Journal of Geophysical Research, 108, 3387, doi:10.1029/2002JC001319, 2003.

Yu, Y. and Rothrock, D. a.: Thin ice thickness from satellite thermal imagery, Journal of Geophysical Research, 101, 25 753, doi:10.1029/96JC02242, 1996.

Zhang, J. and Rothrock, D. a.: Modeling Global Sea Ice with a Thickness and Enthalpy Distribution Model in Generalized Curvilinear Coordinates, Monthly Weather Review, 131, 845–861, doi:10.1175/1520-0493(2003)131, 2003.

Zuo, H., Balmaseda, M. a., Boisseson, E., and Hirahara, S.: A New Ensemble Generation Scheme for Ocean Analysis, ECMWF Tech Memo, 795.

Zuo, H., Balmaseda, A. M., and Mogensen, K.: The new eddy-permitting ORAP5 ocean reanalysis: description, evaluation and uncertainties in climate signals, Climate Dynamics, pp. 1–21, doi:10.1007/s00382-015-2675-1, 2015.