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The Cryosphere Discussions

Interactive comment on "Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data" *by* N. Maaß et al.

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Our sincere thanks go to the anonymous referee #1 who provided us with very useful comments on our paper. The main question 1) was also posed in the specific comments and we here address this question in item 8 below. Regarding the main question 2): We think that the paper in its current and updated version is already quite long and we would prefer to focus on demonstrating that in principle the estimation of snow thickness from SMOS data is possible. Because an operational snow thickness retrieval would involve considerable efforts and is only feasible in the medium term, we would like to address the issue of an operational retrieval in future work. Following your suggestion we have added this statement to the Conclusions (after "A first SMOS snow thickness map showed a realistic distribution of snow thicknesses for the

Arctic."): "For an operational snow thickness retrieval, the assumed values for surface temperature, ice salinity, ice thickness and snow density would not be constant values (as assumed here) but would account for spatial and temporal variations and could be based on climatological estimations, reanalysis data or additional satellite observations. We consider this as future work.". In the following, we address the specific comments given in the review:

1. P3632, L16: Indeed, it is interesting to see how the different model parameters impact the brightness temperature. Thus, we have added the following to the 'Model simulations and sensitivities'-Section:
   "Fig. 1 (see below) shows the sensitivity of brightness temperature to surface temperature, ice thickness, ice salinity, and snow density, in comparison to the sensitivity to snow thickness for the ice conditions encountered during the IceBridge campaign (see Sect. 4). For this first estimation of sensitivity, we assume constant average values for all model parameters except for one, which is varied within a range of values. The corresponding average values, the ranges in which the parameters are varied, and the impact on the brightness temperature are given in Table 1 (see below). We consider the given ranges to be representative for the uncertainties associated with the parameters when these are estimated from satellite observations or a climatology, for example. The uncertainties would be half of the ranges given here. For example, the uncertainty of the MODerate Resolution Imaging Spectroradiometer (MODIS) ice surface temperature product is given to be 1.2–1.3 K (Hall et al., 2004), here we use 2 K. Uncertainty in snow density has been estimated to be 20 $\mathrm{kg\,m^{-3}}$ over multi-year ice and 50 $\mathrm{kg\,m^{-3}}$ over first-year ice (Alexandrov et al., 2011). As a first estimation we here use 40 $\mathrm{kg\,m^{-3}}$ for the snow density's uncertainty. We use an empirical relationship between ice thickness and ice salinity (Cox and Weeks, 1974) to account for the empirical covariance of these two parameters in our simulations. The remaining parameters are varied independently of each other, thus providing a simple mean

to estimate and to compare the different model parameters' impact on brightness temperature. The impact of the snow thickness, which is what we want to retrieve, is the highest (Table 1). When we apply the Gaussian error propagation formula, the sensitivities of brightness temperature to ice thickness, surface temperature, ice salinity, and snow density and their estimated uncertainties result in an uncertainty in brightness temperature of 1.2 K. For the snow thickness retrieval in the range of snow thicknesses 0–40 cm this leads to a snow thickness uncertainty of 8.3 cm for the given ice conditions."

2. P3635, L10: As you pointed out, the SMOS data has to be averaged in order to reduce the noise and to make the measurements applicable for a snow thickness retrieval, considering the sensitivity of brightness temperature to snow thickness. Temporal and spatial averaging is also performed in the retrieval of soil moisture and particularly in the retrieval of ocean salinity from SMOS, which are its main fields of application. To make this point clearer, we have added two sentences in the SMOS data description part, and it reads as follows now: "The radiometric accuracy of single measurements is 2.1 to 2.4 K (M. Martin-Neira, personal communication, 2013). For the retrieval in Sect. 5 we use brightness temperatures averaged over a range of incidence angles and over three days, including on average more than 280 measurements per grid point. Thus, we reduce the mean uncertainty by a factor of $\frac{1}{\sqrt{280}}$ to 0.12 to 0.14 K."

3. P3637, L12: changed. The confusion arose from the numbers given in Table 1 in Farrell et al. (2012), which gives 1 m as the along-track footprint and 268 m as the cross-track footprint.

4. P3637, L17-18: We added the sentence "However, in general, the uncertainty of the ice thickness measurements is variable and depends on the number and distance to sea surface reference points (Kurtz et al., 2013)."

5. P3638, L5: We removed the sentence on 20–60 cm difference, because, as you

clarified, this difference was mainly attributed to the spatial offset between the airborne and in-situ measurements. Instead, we added a further sentence on the uncertainty of the IceBridge snow thickness measurements: "From comparison of the 2009 and 2010 flights with in-situ measurements, the uncertainty of the IceBridge snow thickness has been estimated to be about 6 cm (Kurtz et al., 2013)."

6. P3641, L17-24: We added the sentence "For Arctic applications, the sensitivity to snow thickness is roughly ten times higher than the sensitivity to ice thickness for ice thicknesses of more than approximately 1.5 m." on P3641 and changed the last sentence of the conclusions to "This allows us to reasonably estimate snow thickness from horizontally polarised SMOS brightness temperatures over thick sea ice, here considered as ice thicker than about 1–1.5 m."

7. P3645, L16-17: changed to 'coefficient of determination'

8. Section 4.1: We have added the following sentence to the Discussion part: "We were not able to figure out why our simulations and the observations agreed better at horizontal than at vertical polarisation. We may hypothesize that this is related to the roughness of the ice. However, because our current radiation model does not account for roughness effects, we cannot investigate this at the moment."

9. P3646, L18-21: In the brightness temperature simulations in Figures 3 and 4, the ice thickness and the ice surface temperature, as measured during the IceBridge campaign, are input parameters of the model. In Figures 5 and 6, the ice thickness is still an input parameter, but for the ice surface temperature we used a constant value. There are mainly two reasons, why we used constant values for the ice thickness and the ice surface temperature in the subsequent parts of the study. These are addressed in the following paragraph which we have added to the Discussions section:

"There are mainly two reasons, why we used constant values for the ice thickness and the ice surface temperature in the parts where we retrieved snow thickness from SMOS data. Firstly, we assume that for a potential retrieval of snow thickness from SMOS data in the future, we would not have information on the ice thickness and the surface temperature, at least not for each pixel separately. Thus, we here tried to find out how well the retrieval may succeed when we cannot prescribe ice thickness and temperature accurately in the retrieval model. Secondly, when comparing Figures 5 and 6 with Figures 3 and 4, we see that the variable ice surface temperature has a quite large impact on the variability of the simulated brightness temperatures, not necessarily matching the variability of the SMOS observations. Several reasons are conceivable for the lower agreement when accounting for the variability of surface temperature: 1) the temporal and/or spatial offset between the IceBridge and the SMOS data, which were averaged over 3 days, 2) an incompletely incorporated relationship between the surface temperature, its variability and the bulk ice temperature in the model, or 3) uncertainties in the IceBridge temperature measurements, for example."

10. P3648, L8: changed to "This is in accordance with reports about problems with the SMOS brightness temperature processor that cause brightness temperatures for low incidence angles to be 3–5 K too low (M. Martin-Neira, personal communication, 2013)."

11. P3649, L3-4: changed

12. P3649, L3-18: We are not entirely sure whether we have understood this question correctly. The ranges in which we varied the ice parameters for the SMOS snow thickness retrieval do not (necessarily) represent the variability of the values as measured during the IceBridge campaign, but are rather assumptions we may make for the retrieval if we had no information on ice thickness and surface temperature from the IceBridge campaign. This passage reads as follows now:

"For the retrieval we use different constant values within a range that we would consider to be realistic for the considered time and area, if we did not know the actual conditions during the flight campaign. In our brightness temperature simulations for the snow thickness retrieval, we choose the surface temperature to take values between -40.15 and -33.15 C, the ice salinity is 1.5 or 2.5 $\mathrm{g\,kg^{-1}}$, the ice thickness is between 3 and 5 m, and the snow density takes values between 200 and 320 $\mathrm{kg\,m^{-3}}$."

13. P3649, L23: changed

References

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Table 1. The ice parameters r influencing the brightness temperature, their average values $\overline{r}$ (as used in Fig. 1 for all parameters except for the one that is varied), the ranges in which the parameters are varied Δr, and the impact on the brightness temperature ΔTB.

r	$\overline{r}$	Δr	ΔTB [K]
d_{ice}	4 m	2 m	0.5
d_{snow}	20 cm	40 cm	5.6
T_{surf}	−33.15 C	4 K	1.4
S_{ice}	1.5 g kg^{-1}	2 g kg^{-1}	1.0
ρ_{snow}	260 kg m^{-3}	80 kg m^{-3}	1.5

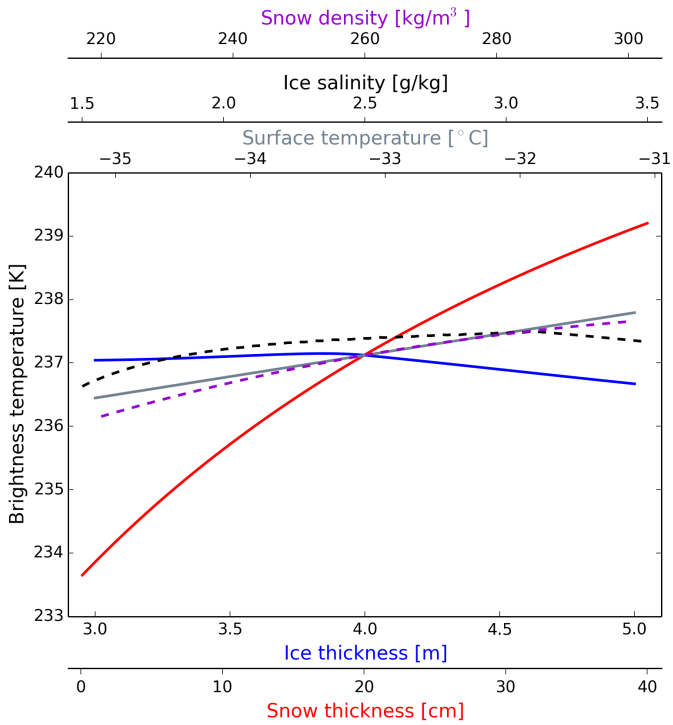

Fig. 1. Horizontally polarised brightness temperature (incidence angle θ= 45{\degree}) as it varies with ice thickness, snow thickness, surface temperature, ice salinity, or snow density, respectively.