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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.

N. Maaß et al.

nina.maass@zmaw.de

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We are very grateful to referee #2 for his helpful comments. In the following, we address the specific comments given in the review:

1. We added the following to the "Emission Model"-Section: "The input parameters used in our model are average bulk values. Because ice temperature and salinity, as well as snow density are usually not constant throughout the ice and snow pack of sea ice (e.g. Cox and Weeks (1974), Eicken (1992), Massom et al. (1997)), using bulk values is a simplification that introduces uncertainties (Tonboe , 2013). However, with our current model we cannot estimate the impact of vertical variations in the ice, because the model neglects higher order reflection

terms. Thus, introducing multiple layers within one medium (i.e. layers with only slightly differing permittivities) leads to brightness temperature changes that are higher than the changes caused by the vertical variations in the ice conditions. As a first approximation, the sensitivity of the brightness temperature to the changing bulk values of snow density, ice temperature, and salinity (Fig. 3) may be used to get an idea of the total impact of these quantities, although the influence of their vertical distribution cannot be studied explicitly with the current model." The figure that is referred to is the one shown in the answer to referee #1.

2. see answer to item 1. Besides, we expect the (absolute) variation of ice salinity in thick multi-year ice to be somewhat smaller than in first-year ice (e.g. Schwarzacher (1959), Eicken et al. (1995)).

3. We are not entirely sure whether we have understood this question correctly. The dielectric properties of sea ice do depend on the orientation and shape of the brine inclusions (Vant et al., 1978). However, here we used an empiric formula that relates the permittivity of sea ice to its brine volume fraction, as presented in Vant et al. (1978). This empiric model is based on measurements taken in sea ice in the Arctic. As the model is empirical, it does not explicitly describe the shape and orientation of the brine inclusions, but rather gives an effective permittivity as observed in naturally occurring sea ice. The difference between horizontally and vertically polarised brightness temperatures, as seen in our study, does not reflect the orientation of any ice particles, but originates from the definition of horizontal and vertical polarisation. At nadir view (θ= 0°) they are identical; for incidence angles $\theta > 0°$, electromagnetic energy can be divided into a horizontally and a vertically polarised component. For all media, the horizontally and vertically polarised brightness temperatures are functions of the incidence angle, and the shape of this function depends on the considered media's permittivities (see p. 231 of Ulaby et al. (1981), for example).

4. changed to "coefficient of determination" (see answer to comment no. 7 of referee #1)

5. We added the following sentence 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.". (see answer to main question 2) of referee #1)

6. We added the following to the "Emission model"-Section: "The radiation is assumed to be incoherent, i.e. the layers' thickness variations within the illuminated footprint are considered to be large enough to destroy interference effects (Menashi et al., 1993). The surfaces of the layers are assumed to be smooth."

7. We added the following to the Discussions-Section: "Finally, we try to assess the applicability of our SMOS snow thickness retrieval to Antarctic sea ice. On the one hand, the generally higher ice salinity of Antarctic sea ice causes the brightness temperature to saturate more rapidly with regard to the brightness temperature's sensitivity to ice thickness. This results in a broader range of ice thicknesses to be suitable for the snow thickness retrieval from L-band brightness temperatures. On the other hand, several conditions would make the retrieval more difficult than for Arctic sea ice: The more divergent ice cover in the Antarctic causes ice concentrations to be more variable, which introduces large uncertainties to the retrieval. Furthermore, the often wet snow cover and the less distinct transition between ice and snow at the ice-snow-interface are likely to be unfavourable for the retrieval of snow thickness from SMOS data in the Antarctic."

8. In the part where we compare simulated and observed brightness temperatures,

we take into account the ice thicknesses and ice salinities. However, in the part where we retrieve snow thickness from SMOS brightness temperatures, we try to keep the assumptions as uniform and as simple as possible (in order to focus on the impact of snow thickness, not of the other ice parameters). Therefore, we set the average ice thickness and ice salinity in the model simulations to constant values. However, we limited the comparisons to cases where the IceBridge measurements showed ice thicknesses of more than 1 m. Obviously, we forgot to mention this in the text and have added the following in the beginning of section 5: "According to our theoretical considerations, we expect this potential to be given only for relatively thick ice. Thus, in the following we exclude all IceBridge pixels with average ice thicknesses of less than 1 m."

- P3628, L17: changed as suggested
- P3634: We have added the following to the "Emission model"-Section: "The range of values we consider for these input parameters are as following: Because the impact of snow thickness on L-band brightness temperatures is negligible for thin sea ice, we here focus on sea ice having thicknesses of more than 1 m. Depending on the season, 75 to 90% of the ice thicknesses in the Arctic are above this value of 1 m (Bourke and Garrett, 1987), although this fraction may have decreased due to a thinning of the ice cover (e.g. Rothrock et al. (1999)). The bulk ice salinity of sea ice with a thickness of 1 m has been observed to be about 6.3 $g\,kg^{-1}$ and to decrease to 1.5 $g\,kg^{-1}$ for ice thicknesses of 4 m (Cox and Weeks, 1974). The average snow density in the Arctic has been measured to vary between 250 $kg\,m^{-3}$ in September and 320 $kg\,m^{-3}$ in May (Warren et al., 1999). The simulation model works best for cold ice temperatures and we expect large uncertainties during the melting season. Thus, we focus on ice surface temperatures below the freezing point and accordingly to a dry snow cover."
- P3637, L12: replaced by "The ice thickness measurements with the ATM laser

altimeter have a circular footprint of about $1\,\text{m}$ size (Kurtz et al., 2013)." (see answer to comment no. 3 of referee #1)

- P3637, L25: added reference Farrell et al. (2012)
- P3638, L5: We removed the sentence on 20–60 cm difference, because, as pointed out by both referees, 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)." (see answer to comment no. 5 of referee #1)
- P3638, L23: The results are indeed similar. However, the snow density value we used throughout the study ($\rho_{snow} = 260\,\text{kg}\,\text{m}^{-3}$) was based on a value used in Farrell et al. (2012), which had been obtained for field measurements near the coast of Greenland, while we consider a large area in the Arctic here. Thus, in agreement with the average snow density used in Kurtz et al. (2013), we recalculated all analyses using the value $\rho_{snow} = 320\,\text{kg}\,\text{m}^{-3}$, which is the climatological average value for the Arctic in March (Warren et al., 1999).
- P3639, L24: changed to "... but we state that at nadir view (θ= 0°) the impact of a snow layer on the brightness temperature is about the average of the increases at horizontal and at vertical polarisation shown here for θ= 45°." in order to emphasize that we mean the average of the two curves for the two polarisations.
- P3640, L28: changed as suggested
- P3641, L24: changed as suggested
- P3642, L11-13: changed to "The bulk ice salinity for the SMOS grid cell is estimated from the mean ice thickness using an empirical relationship between ice

salinity and ice thickness in the Arctic ..."

- P3642, L25: see answer to item P3638, L23 above
- P3643, L7: changed as suggested
- P3646, L18: There are mainly two reasons, why we used constant values for the ice thickness (and the ice surface temperature) here and in the snow thickness retrieval part. These are addressed in the following paragraph, which we 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, the first one representing values measured within minutes, the latter one having been averaged over 3 days, 2) an incompletely incorporated relationship between the surface temperature, its variability and the bulk ice temperature in the model, and 3) uncertainties in the IceBridge temperature measurements, for example." (see answer to comment no. 9 of referee #1)
- P3647, L20: changed as suggested

- P3648, L9: 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)." (see answer to comment no. 10 of referee #1)
- P3649, L12: changed to "bulk ice salinity"
- P3651, L10: added reference Kwok et al. (2011)
- P3655, L12: see answer to item 6 above.
- P3655, L20: Indeed, that may have occurred. We added "Thus, the snow could partly be wet, contradicting our assumption of dry snow."

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