

Interactive comment on “Estimating Snow Depth on Arctic Sea Ice using Satellite Microwave Radiometry and a Neural Network” by Anne Braakmann-Folgmann and Craig Donlon

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We would like to thank Eero Rinne for his insightful comments and for opening the discussion.

I am really happy to see work on high priority Copernicus polar mission candidates to come out - especially work pointing out synergies between different candidates. In short, the paper presents a novel way to derive the thickness of snow on sea ice – a parameter that is one of the key uncertainty contributors to sea ice thickness altimeter retrievals. Passive microwave based snow product from CIMR could complement the snow thickness estimate the dual frequency altimeter product of CRISTAL, latter being

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of superior resolution but worse coverage. For single frequency altimeters like Cryosat-2 and Sentinel 3 the impact of a novel PMW snow estimate, like the one presented in this paper, would be much larger than for CRISTAL. Whenever a new snow product emerges, it is tested against the Warren 1999 (W99) climatology, as this manuscript has done. However, I feel that there are significant shortcomings in the way W99 is handled in this paper. Most importantly, instead of the original W99, the authors should use the modified W99 which accounts for thinner snow on FYI. All of the current CS2 SIT products use the modified W99. Reason for this is that as authors point out, original W99 has been shown to give too thick snow over the FYI areas covered by OIB by Kurtz et al. A comparison of CS-2 SIT using modified W99 and OIB SIT can be found in for example in Tilling et al 2018 (<https://doi.org/10.1016/j.asr.2017.10.051>) where the two agree within 0.5 cm. This is in stark contrast with the 24 cm bias in table 3. Key point of the manuscript is that the new snow product is better than the original W99. Real question is, however, if the novel snow product is better than the modified W99 currently used for the CS-2 SIT retrievals. The authors should, in my opinion, add this comparison in the next version.

In the revised version of the paper, we are using the modified W99 climatology in addition to the original one. This indeed leads to an improved agreement with the OIB data, but does not change our conclusions. Our RMSE between the modified W99 and OIB are in agreement with the one reported by Tiling et al. 2018 (0.66 m and 0.67 m). Our bias (0.16 m) is indeed higher, but we do not expect to reproduce their numbers, since a few processing steps differ and we compare results for 2013-2015, while they compare their estimates with OIB data from 2011-2013. Apart from a very good agreement with OIB, they also retrieve a bias of 0.21 m compared to CryoVex, so we believe our results are plausible.

Adding a comparison to the modified Warren climatology leads to the following additions in the paper: In section 2.5 (p.9, ll. 17-18): “[The last - and a major - uncertainty in the calculation of SIT is snow depth h_s (Zygmuntowska et al. (2014),

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Giles et al. (2007)). Here we use the] **original Warren climatology, its modified version where snow depth is halved over FYI and the algorithms from [. . .].**”

In section 3.5.2 (p.12, l.7): “The same product is also used to modify the Warren climatology. In areas of FYI we half the original snow depth values.”

In section 4.2 another line was added to the table and an additional subplot was added to Figure 9 and 10 to include the modified Warren climatology. In the text we added the following part (p.19, l. 15): “For the Warren climatology we observe that the modified version performs better in all the categories, but still worse than most other algorithms.”

Also a citation was added (p.25, l.22): “Kurtz, N. T. and Farrell, S. L.: Large-scale surveys of snow depth on Arctic sea ice from operation IceBridge, Geophysical Research Letters, 38, <https://doi.org/10.1029/2011GL049216>, (2011)”

Furthermore, the authors begin their SIT processing from a freeboard product in the Cryosat-2 GDR. It is reasonably hard to find the details of the processor, but the freeboard is most likely already corrected for the propagation speed of radar pulse in snow. For this, a snow estimate has been required. Authors should remove the propagation speed correction and calculate another with their own snow estimate. Or if there is no propagation speed correction in the GDR freeboard estimate, one must be applied before FB to SIT conversion.

This is a valid point and we put a considerable amount of effort into finding out the details of the GDR processing. The official statement from EOhelp on the propagation speed correction is, that they don’t do any. Adding a snow propagation speed correction to the freeboard data, however, results in a considerable bias independent of the snow product used. In a paper by Kwok (2014), the effect of both such a snow delay correction and snow penetration correction are discussed.

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We included these findings in chapter 2.5 (p.9, l.20): “For the calculation of sea ice freeboard h_{fb} from radar freeboard h_{rfb} two corrections should be applied (Kwok (2014)). The first correction dh_p accounts for penetration issues caused by the scattering of the Ku-band radar signal at the air-snow interface and within the snow layer. This shifts the retracking point closer to the satellite. The second correction dh_d adjusts the radar freeboard for the slower propagation speed of the radar signal within a snow layer:

$$h_{fb} = h_{rfb} + dh_p + dh_d$$

Both corrections have opposite signs and therefore more or less cancel out depending on the snow depth, the retracker and the ratio between the snow-ice and snow-air interface peaks (Kwok (2014)). It is especially hard to apply the first correction, since the ratio between the snow-ice and snow-air interface peaks is not known. Kwok’s simulations suggest that for snow depths of 5-30 cm (which covers a major part of the OIB data) both corrections add up to 0.2 cm on average and are almost independent of snow depth, when a leading edge retracker is used. Therefore we apply a joint correction of 0.2 cm to all CryoSat radar freeboard data.”

The uncertainty arising from this mean correction is again mentioned in the discussion in 4.2 (p.21, l.9): “Additionally we only apply a mean correction for the combined effect of radar penetration and radar delay caused by the snow pack. The sign and magnitude of this combined correction, however, depend on the snow depth and primarily the ratio between the snow-ice and snow-air interface peaks. The lack of data for the latter add to the uncertainty budget of SIT.”

The citation was added as well (p.25, l.25): “Kwok, R.: Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard, *Geophysical Research Letters*, doi:10.1002/2014GL060993 (2014)”