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The Cryosphere
Discussions

# *Interactive comment on* "Estimating the snow depth, the snow-ice interface temperature, and the effective temperature of Arctic sea ice using Advanced Microwave Scanning Radiometer 2 and Ice Mass Balance buoys data" *by* Lise Kilic et al.

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**Response to reviewer 1**

**We thank the reviewer (Leif Toudal Pedersen) for his helpfull comments, which improve the paper with better explanations of the methodology and important discussion about the ice types.**

General comments



More discussion about the impact of ice type on the results should be included. The Markus & Cavalieri snow depth algorithm is only supposed to work properly over first year ice, most of the OIB and IMB data are from areas of multi-year ice. These issues and their impact on the results should be more clearly identified and discussed.

**We have included an analysis of the ice type, and removed the comparison with Markus and Cavalieri algorithm. The IMB are located only on multiyear ice, and OIB campaigns cover first year ice and multiyear ice. We add the ice type information in Figure 3, and discuss the results in section 3.2.**

There should be a clearer wording about when the results for Tsnow-ice are derived using in-situ snow depth and when they are derived using the estimated snow-depth from this study. Both in the abstract and in the conclusions, error numbers assuming in-situ snow depth measurements are given, but these are not generally available, so the uncertainties for the retrievals using satellite snow depths are generally more relevant.

**We have remplaced the error numbers in the abstract and in the conclusion, giving the results obtained using the snow depth regression.**

The concept of effective temperature is based on an assumption of constant emissivity. It is here even referred to as surface emissivity. In reality the emissivity varies with depth as does the temperature, and in particular the emissivity at the surface is small since the emissivity of snow is very small during Winter (no absorption = no emissivity). It should be better explained what is actually the emissivity referred to as the surface emissivity, and some considerations about its variability with temperature and salinity for example would be appreciated.

**Further explanations have been added in the introduction with an equation:**

**"The surface contribution i.e., the surface brightness temperature (TB) depends on frequency and it is the product of the surface effective emissivity ($e_{eff}$) and**

**the surface effective Temperature ($T_{eff}$):**

$$TB = e_{eff} \cdot T_{eff} \quad (1)$$

**"$T_{eff}$ is defined as the integrated temperature over a layer corresponding to the penetration depth at the given frequency: the larger the wavelength, the deeper the penetration into the medium. In the same way, eeff represents the integrated emissivity over a layer corresponding to the penetration depth. It depends on the frequency, on the incidence angle, and, on the sub-surface extinction and reflections between snow and sea ice layers (Tonboe, 2010)."**

More detailed comments:

P1L20: Sea ice dynamics and thermodynamics -> Sea ice thermodynamics

**Done.**

P2L1: reduced -> reduces

**Done.**

P2L9: Advance -> Advanced

**Done.**

P2L11 and reference section: The RRDP should be referred to as Pedersen et al, 2018, https://figshare.com/articles/Reference_dataset_for_sea_ice_concentration/6626549

**Thank you, we add the reference.**

P2L24: In principle this should also be "surface effective emissivity" (see above), and it should be better explained how to estimate this emissivity.

**Better explanation has been added (see my response above).**

P3L5: See comment P2L11 above

**Reference added.**



P3L10-11: Note that neither the OIB nor the IMB data in the RRDP are guaranteed 100% ice. This should be considered and the impact on the results should be discussed.

**We verified this point. Using a SIC algorithm on Tbs (6V and 6H) at IMB position, the SIC is between 95% and 100% for all the measurements. For the OIB the SIC is also between 95% and 100% (with some lower values at 70-80%).**

P3L15: See P2L11 above. In addition the resolution matching of AMSR2 is carried out by JAXA and should be referred to as Maeda et al, 2011 Maeda, K., Y. Taniguchi and K. Imaoka, (2016), GCOM-W1 AMSR2 Level 1R Product: Dataset of Brightness Temperature Modified Using the Antenna Pattern Matching Technique, IEEE Transactions on Geoscience and Remote Sensing, VOL. 54, NO. 2.

**The references have been added.**

P3L19-20: The acoustic sounder only measures the position of the snow surface. The position of the ice surface is assumed from deployment or from the Summer measurements at the end of the ablation period. The sensor is mounted on a pole frozen into the ice, looking down at the snow surface. It measures distance between the instrument and the snow surface, thus recording the changes in the snow depth.

**On the CRREL website (http://imb-crrel-dartmouth.org/imb/), it is explained that the acoustic sounder measures the snow and the ice surface position as well as the ice bottom position. See also Richter-Menge, J. A., Perovich, D. K., Elder, B. C., Claffey, K., Rigor, I., & Ortmeyer, M. (2006). Ice mass-balance buoys: a tool for measuring and attributing changes in the thickness of the Arctic sea-ice cover. Annals of Glaciology, 44, 205-210. The reference has been added to the text.**

P3L21: IMB buoys -> IMBs. The B in IMB means Buoy and does not have to be repeated. There are many instances of this in the text.

**Ok. It has been corrected throughout the text.**

P3L23: bouys -> buoy

**Done.**

P3L29: OIB radar -> the OIB snow radar. OIB operates other radars as well.

**Done.**

P5L1-5: Please include a bit more details about the simulated data, such as number of datapoints, types of ice etc.

**We added more explanations:**

**"For the estimation of $T_{eff}$, we use a microwave emission model coupled with a thermodynamic model. The emission model uses the temperature, density, snow crystal and brine inclusion size, salinity, and snow or ice type to estimate the microwave emissivity, the $T_{eff}$, and the TB of sea ice. It is coupled with a thermodynamic model in order to provide realistic microphysical inputs. The thermodynamic model for snow and sea ice is forced with ECMWF ERA40 meteorological data input: surface air pressure, 2m air temperature, wind speed, incoming shortwave and longwave radiation, relative humidity, and accumulated precipitation. It computes a centimeter scale profile of the parameters used as inputs to the emission model. The emission model used here is a sea ice version of the Microwave Emission Model of Layered Snowpacks (MEMLS) (Wiesmann et al., 1999) described in Matzler et al., 2006. The simulations were part of an earlier version of the RRDP and the simulation methodology is described in Tonboe et al., 2010. This MEMLS simulation uses among its inputs the snow depth and the $T_{Snow-Ice}$ and compute $T_{effs}$ and TBs at different frequencies (from 1.4 to 183 GHz). The dataset contains 1100 cases and is called the MEMLS simulated dataset in the following."**

P5L30: satisfying -> satisfactory

**Done.**



P6L1-10: Discuss also the potential for a seasonal variation in the regression. OIB data are all from late Winter to Spring, whereas the IMB data are for all Winter. What impact could that have, and why do you expect your regression from OIB to work also during other parts of the Winter.

**The final regression for snow depth (eq 1) is computed from IMB data. The OIB data are used only for the channel selection. Therefore the regression can not be appropriate out of the winter period. We add a discussion in the results about the impact of the season on the snow depth regression for OIB data. "It is also important to note that the OIB campaign data are from late winter to beginning of spring, while IMB measurements are from winter. The snow depth regression being developed on IMB measurements, this small change in the season can contribute to the larger RMSE observed with OIB data"**

P6L21-27: Here you need to discuss why you think the Markus and Cavalieri snow depth algorithm can be applied to MY-ice.

**We know that the Markus and Cavalieri snow depth algorithm has been designed for Antarctic where the sea ice is mostly first year and young ice. The Markus and Cavalieri algorithm is based on physical and radiative properties of the snow using the 18 and 36 GHz frequencies, and we only used it to give a comparison with our algorithm. Our goal was not to evaluate the Markus and Cavalieri algorithm, so we removed it, as you suggested, because it was confusing.**

P6L31: Please provide a reference to the OIB uncertainties quoted here. Also note that the RRDP OIB dataset contains information about the variability of the snow depth over the 50 km sections. This could have been used to filter out the OIB data with too much variability. The RRDP also contains ASCAT C-band scatterometer data that could be used to distinguish ice types.

**It is the standard deviation of the OIB snow depth given in the dataset with the snow depth itself. We have added the information in the text.**

Figure 2: You should not apply the Markus and Cavalieri algorithm to MY-ice and you should discuss the importance of ice type for your own snow depth retrievals.

**We removed Markus and Cavalieri results and added the ice type information and a discussion about it. For our retrieval, the use of the 6GHz channel limits the problem of the ice type as there is not a big change in emissivity between first year and multiyear ice at this frequency.**

P7L7-8: The temperature gradient is a function of the thermal conductivities and the depth of snow and ice respectively. The temperature gradient in snow is certainly not always 35 K/m! Please rephrase this sentence.

**Yes, we removed it. That was only for one case.**

Section 4.1: This methodology is rather crude. It assumes thermodynamic equilibrium (which is not always the case, please discuss), and it could have been refined to a better estimate of the snow/ice interface temperature by the method outlined in section 4.1.5 of the RRDP manual (identifying the crossing point of the linear temperature profile in ice and in snow respectively). This might have reduced the quantization "noise" in the IMB Tsnow-ice data.

**The methodology we use is based on the same principle that the method you described in the RRDP manual. We compute the first derivative of the temperature profile to obtain the tangent then the second derivative is used to compute the variation in the temperature gradient and to identify the level in the thermistor string where the change of medium is happening. We can not use exactly the method you described as we have no a priori about which thermistor belongs to the snow and which thermistor belongs to the ice. The methodology has been designed for winter profiles and the limitations of this method are described in section 4.1.**

P10L5-14: Equations (2), (3) and (4) do not make sense as they stand. The TBs should



have been delta-TBs and you should specify the center TBs you subtracted to get to the delta TB and you should more clearly specify that these are NOT Tbs.

**These are Tbs. In the equations (2),(3),(4) we use the brightness temperature at 10V and 6V. To obtain this expression, a first step was to use the centered TB to compute the variation of the Tsnow-ice only induced by the TB. Then we use directly the TB to compute the snow depth dependence and so the final equation. We added explanations:**

**"To express the $T_{Snow-Ice}$ as a function of the TB at 6V and 10V, the linear regressions are calculated on centered data. For each buoy, the averaged $T_{Snow-Ice}$ is subtracted from the $T_{Snow-Ice}$ measurements (the same is done with the TB measurements). Thus, the temperature offset between the buoys is removed and the slope in the linear regression is unchanged.**

$$\Delta T_{Snow-Ice} = a_1 \cdot \Delta TB_{6V or 10V} \Leftrightarrow T_{Snow-Ice} = a_1 \cdot TB_{6V or 10V} + offset_{buoy} \quad (2)$$

**with $\Delta T_{Snow-Ice}$ and $\Delta TB$ describing the centered $T_{Snow-Ice}$ and TB."**

P11L5-7: This should have been mentioned earlier and could have been fixed by applying the method from the RRDP manual described above under Section 4.1.

**The problem specified here is that the vertical resolution of the thermistor string is 10cm, and the interface may not be exactly at the position of the thermistor. Even if we know exactly the position of the interface, we will need to extrapolate the temperature and this should be discuss as well.**

P12L3: Explain a bit more what Teff is and why you need simulated data.

**An explanation has been added. "Teff is related to the frequency and the incidence angle of the observations. It is not a geophysical variable that we can measure directly as an in situ parameter. A microwave emission model has to be used to computed the T ef f s from the geophysical parameters."**

P12L4: are simulated together -> are all simulated

**The sentence has been modified.**

P12L10: simulated data -> simulated TB data **Done.**

P12L13-15: These biases are presumably in the MEMLS simulations and not in the TB data, so you should bias-correct the MEMLS simulations and not the AMSR2 TB data.(This applies to figure 10)

**Here, we do not bias-correct the AMSR2 TB data. We are expressing the Tsnow-ice from MEMLS dataset as a function of the Tsnow-ice estimated from our regression (eq 3 and 4) using the TBs contained in the MEMLS dataset. We obtain an equation as follow:**

$$T_{snow-ice\ MEMLS} = Tsnow - ice - -3.97. \tag{3}$$

**Then in the following we derive the expression of Teff as a function of T$_{snow-ice\ MEMLS}$:**

$$Teff_{freq,v} = b1 \cdot T_{snow-ice\ MEMLS} + b2 \tag{4}$$

**Finally, if you want to derive the effective temperature from AMSR2 TBs you want to replace the T$_{snow-ice\ MEMLS}$ by T$_{snow-ice}$:**

$$Teff_{freq,v} = b1 \cdot (T_{snow-ice} - 3.97) + b2 \tag{5}$$

**The expressions have been added in the text to make this clearer to the reader.**

P12L20-21: Explain more (f.ex using a reference) why H pol TBs are more noisy??

**We add a explanation. Variability of the sea ice Tbs at microwave frequencies is larger in horizontal polarization that is much more sensitive to dielectric changes and to roughness (see Kilic et al. 2018).**

Figure 11: The figure text must be wrong. This figure must be for only one frequency (which)?



**It has been corrected.**

P13L4+5: As stated in the general comments, all layers emit, to the concept of "an" emitting layer is an abstraction and should be explained more carefully.

**The concept of emitting layer has been replaced by penetration depth: "A slope coefficient lower than 1 means that the penetration depth at the given frequency is deeper than snow-ice interface. At 50 GHz the slope coefficient is close to 1, meaning that the penetration depth is close to the depth of the snow-ice interface."**

P13L8: section -> sections

**Done.**

P14L10-11: According to Warren (1999) the snow depth in general is not supposed to decrease from November to January, so this reference seems wrong. If this behavior is seen in certain regions please be more specific.

**The paragraph has been re-written. "The results show that the snow depth is larger (40 cm) in the north of Greenland (Warren et al., 1999 ; Shalina and Sandven, 2018) due to the presence of drift snow caused by the numerous pressure ridges present in this area (Hanson, 1980), as anticipated. We can observe that the snow depth is larger in areas with larger multiyear ice concentrations. The variability of the snow cover is low during winter, as the snow depth reach a maximum by December and remains relatively unchanged until snowmelt (Sturm et al., 2002)."**

P16L6: The U-Bremen MY-ice fraction is NOT "completely independent" since it uses microwave radiometer data (AMSR2 or SSMIS) at the same polarizations and frequencies as the current study.

**Yes, it is the method which is independent. "an independent work done at the University of Bremen and distributed daily to users. However it should be noted**

**that the input channels of both methods overlap in some AMSR2 channels, and even different channels show some covariance (Scarlat et al., 2017)."**

P16L14: A RMSE -> An RMSE

**A root mean square error**

P16L14: on the estimated snow depth -> between the estimated and reference snow depths

**Done.**

P16L15: and the snow depth -> and in-situ snow depth And you should quote the results obtained using your estimated snow depth as well since in-situ snow depths are not generally available

**Yes, it has been replaced by the figures using the estimated snow depth.**

The discussion lacks considerations about the importance/impact of ice type.

**We have added a discussion about the ice types. "A RMSE of 5.1 cm is obtained between the estimated and the IMB snow depths. This snow depth retrieval is applicable for FYI and MYI, with lower uncertainties for FYI than for MYI (3.9 cm compared to 7.2 cm)." and "The errors obtained are 2.87 K and 2.90 K respectively at 10V and 6V. This $T_{Snow-Ice}$ retrieval has been tested only for MYI. It can also be applied over FYI as the 6V and 10V channels are not sensitive to the ice type (Spreen et al., 2008)."**