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

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Abstract. Mapping Sea Ice Concentration (SIC) and understanding sea ice properties and variability is important especially today with the recent Arctic sea ice decline. Moreover, accurate estimation of the sea ice effective temperature (T_{eff}) at 50 GHz is needed for atmospheric sounding applications over sea ice and for noise reduction in SIC estimates. At low microwave frequencies, the sensitivity to atmosphere is low, and it is possible to derive sea ice parameters due to the penetration of microwaves in the snow and ice layers. In this study, we propose simple algorithms to derive the snow depth, the snow-ice interface temperature ($T_{Snow-Ice}$) and the T_{eff} of Arctic sea ice from microwave brightness temperatures (TBs). This is achieved using the Round Robin Data Package of the ESA sea ice CCI project, which contains TBs from the Advanced Microwave Scanning Radiometer 2 (AMSR2) collocated with measurements from Ice Mass balance Buoys (IMBs) and the NASA Operation Ice Bridge (OIB) airborne campaigns over the Arctic sea ice. The snow depth over sea ice is estimated with an error of **5.1 cm** using a multilinear regression with the TBs at 6V, 18V, and 36V. The $T_{Snow-Ice}$ is retrieved using a linear regression as a function of the snow depth and the TBs at 10V or 6V. The Root Mean Square Errors (RMSEs) obtained are **2.87 and 2.90 K** respectively, with the 10V and 6V TBs. The T_{eff} at microwave frequencies between 6 and 89 GHz is expressed as a function of $T_{Snow-Ice}$ using data from a thermodynamical model combined with the Microwave Emission Model of Layered Snow-packs. T_{eff} is estimated from the $T_{Snow-Ice}$ with a RMSE of less than 1 K.

1 Introduction

In situ observations of the variables controling the sea ice energy and momentum balance in polar regions are scarce. One way to overcome this observational gap is to use satellites for measuring sea ice properties. **The objective of this study is to estimate key sea ice variables from satellite remote sensing to improve current sea ice models and prediction, Sea Ice Concentration (SIC) mapping in the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSISAF) project, and polar atmospheric sounding applications.**

Sea ice thermodynamics is controlled by the regional heat budget (Maykut and Untersteiner, 1971). In general, sea ice is covered by snow, which can reach a mean thickness of up to ∼50 cm in the Arctic (Sato and Inoue, 2018). Snow on sea ice strongly affects the sea ice energy and radiation balance, with its high insulation of heat and reflectivity of solar radiation. Snow is a poor conductor of heat: it insulates the sea-ice and reduces the winter ice growth (Fichefet and Maqueda, 1999). In summer, its high albedo reduces the sea-ice melting rate. **The high albedo of snow on sea ice compared to open water albedo plays an important role in the sea ice albedo feedback mechanism and Arctic amplification (Hall, 2004).** Sato and Inoue (2018) suggest that the recent sea ice growth has been effectively limited by the increase in snow depth on thin ice during winter. Current sea ice models include snow schemes (e.g., Lecomte et al. (2011)), with the snow depth and temperature gradient in the snow pack modulating the sea ice growth and melt. Improved estimates of Snow Depth (SD), as well as Snow-Ice interface Temperature ($T_{Snow-Ice}$) from satellite observations would provide valuable information on the vertical thermodynamics in the snow and ice, to improve current sea ice models and therefore the prediction of sea ice growth.

Here we propose a simple algorithm to retrieve SD and $T_{Snow-Ice}$ from passive microwave observations from the Advanced Microwave Scanning Radiometer 2 (AMSR2), based on a large dataset of collocated *in situ* and satellite observations. **An extensive Round Robin Data Package (RRDP) (Pedersen et al. (2018),https://figshare.com/articles/Reference_dataset_for_sea_ice_concentration/6626549) has been developed during the European Space Agency (ESA) sea ice Climate Change Initiative (CCI) project and the SPICES (Space-borne observations for detecting and forecasting sea ice cover extremes) project (http://www.seaice.dk/ecv2/rrdb-v1.1/).** It contains *in situ* data from the Ice Mass balance Buoys (IMBs), and the Operation Ice Bridge (OIB) airborne campaigns collocated with AMSR2 brightness temperature measurements between 6 and 89 GHz.

Algorithms already exist to retrieve the snow depth from microwave observations. Markus and Cavalieri (1998) and Comiso et al. (2003) use the spectral gradient ratio of the 19 and 37 GHz (GR37/19) in vertical polarization to deduce the snow depth over sea ice. **This method has been developed for dry snow on First Year Ice (FYI) in Antarctica, and it is applicable only to this ice type. Sea ice emissivity depends on the ice type. At frequencies $\geq$ 18 GHz, the ice emissivity is higher for FYI than for Multi Year Ice (MYI) (Spreen et al., 2008). The difference of emissivity between the 19 and 37 GHz can be used to retrieve the snow depth or the sea ice type. Therefore, the snow depth algorithms which use this gradient ratio (GR37/19) are strongly dependent to the ice type. Improvements of Markus and Cavalieri (1998) have been suggested by Markus et al. (2011) and Kern and Ozsoy-Çiçek (2016). More recently, Rostosky et al. (2018) revisit the methodology for the Arctic region, using a new gradient ratio between 7 and 19 GHz (GR19/7), to derive snow depth over both FYI and MYI. For their study, they use the snow depth of OIB campaigns obtained in March and April. With the help of the RRDP, we will extend the methodology to the full winter (from December 1st to April 1st) for the Arctic region using the IMB snow depth data.**

Tonboe et al. (2011) showed from radiative transfer simulations that there is a high linear correlation between the $T_{Snow-Ice}$ and the passive microwave observations at 6 GHz. Preliminary results from Grönfeldt (2015) evidenced the possibility to derive the temperature of sea ice from passive microwave observations using simple regression models. This work will be extended here **to estimate $T_{Snow-Ice}$ over Arctic sea ice.**

Passive microwave satellite observations between 50 and 60 GHz are extensively used to provide the atmospheric temperature profiles in Numerical Weather Prediction (NWP) centers, with instruments such as the Advanced Microwave Sounding Unit-A (AMSU-A) or the Advanced Technology Microwave Sounder (ATMS). For an accurate estimation of the temperature profile in the lower atmosphere, quantifying the surface contribution is required. **The surface contribution i.e., the surface brightness temperature (TB) depends on the frequency, and it is the product of a surface effective emissivity (e$_{eff}$) and a 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, e$_{eff}$ represents the integrated emissivity over a layer corresponding to the penetration depth. It depends on the frequency, the incidence angle, and the sub-surface extinction and reflections between snow and sea ice layers (Tonboe, 2010). Therefore, estimating the surface contribution is particularly complicated over sea ice, due to the layering and the vertical structure of the snowpack wich are affecting the microwave emission processes (Mathew et al., 2008; Rosenkranz and Mätzler, 2008; Harlow, 2009, 2011; Tonboe, 2010; Tonboe et al., 2011), and to the large spatial and temporal variability of sea ice and snow cover (English, 2008; Tonboe et al., 2013; Wang et al., 2017). The understanding of the relationship between T$_{eff}$ and the physical temperature profile is complicated, especially at microwave frequencies $\geq$18 GHz when scattering occurs, but it has been shown that from 6 to 50 GHz there is a high correlation between the T$_{eff}$ and the T$_{Snow-Ice}$ (Tonboe et al., 2011). With T$_{Snow-Ice}$ estimated from the AMSR2 observations, we will deduce the sea ice T$_{eff}$ at AMSR2 frequencies between 6 and 89 GHz, using linear regression.

Section 2 describes the dataset and the methodology used in this study. The snow depth retrieval is presented in Section 3. Section 4 reports on the T$_{Snow-Ice}$ retrieval. Finally, microwave sea ice T$_{eff}$ at 50 GHz is derived, for application to temperature atmospheric sounding (Section 5). Section 6 discusses the snow depth and the T$_{Snow-Ice}$ retrieval results over a winter in Arctic. Section 7 concludes this study.

2 Material and Methods

2.1 The database of collocated satellite observations and in situ measurements

The RRDP from the ESA sea ice CCI project is a dataset openly available (Pedersen et al. (2018), https://figshare.com/articles/Reference_dataset_for_sea_ice_concentration/6626549). It contains an extensive collection of collocated satellite microwave radiometer data with *in situ* buoy or airborne campaign measurements and other geophysical parameters, with relevance for computing and understanding the variability of the microwave observations over sea ice. It covers areas with 0% and 100% of SIC and different sea ice types (thin ice, first-year ice, multiyear ice), for all seasons including summer melt. In our study, we will focus on Arctic sea ice during winter in regions with 100% sea ice cover. Two different datasets from the RRDP are used:

Table 1. List of the IMBs used in this study, with the mean snow depth (column 5) and the mean ice thickness (column 6) computed over the duration of the measurements (column 2).

Buoy ID	Duration of measurements during winter (dd/mm/yy)	Deployment location	Position on December 1^{st} (lat; lon)	Mean snow depth (cm)	Mean ice thickness (cm)
2012G	01/12/12 - 06/02/13	Central Arctic	(85,79°; -134,88°)	34.1	162.8
2012H	01/12/12 - 06/02/13	Beaufort Sea	(80,39°; -129,23°)	23.2	173.3
2012J	01/12/12 - 06/02/13	Laptev Sea	(82,87°; 139,09°)	25.5	100.3
2012L	01/12/12 - 06/02/13	Beaufort Sea	(80,36°; -138,55°)	8.5	330.1
2013F	01/12/13 - 31/03/14	Beaufort Sea	(76,15°; -146,27°)	50.3	145.7
2013G	01/12/13 - 31/03/14	Beaufort Sea	(75,84°; -151,46°)	21.3	249.4
2014F	01/12/14 - 11/03/15	Beaufort Sea	(76,32°; -143,10°)	16.1	151.8
2014I	01/12/14 - 12/03/15	Beaufort Sea	(78,52°; -148,70°)	22.6	155.3

AMSR2 brightness temperatures (TBs) collocated with IMB measurements, and AMSR2 TBs collocated with OIB airborne campaign measurements.

AMSR2 is a passive microwave radiometer on board the JAXA GCOM-W1 satellite (launched in May 18, 2012). AMSR2 has 14 channels at 6.9, 7.3, 10.65, 18.7, 23.8, 36.5 and 89 GHz for both vertical and horizontal polarizations and it observes at 55° of incidence angle. In the RRDP, the spatial resolution of each channel is resampled by JAXA to the 6.9 GHz resolution (32×62 km) (see AMSR2 L1R products, Maeda et al. (2011) and Maeda et al. (2016)) before collocation with buoy or airborne campaign measurements (RRDP report, Pedersen and Saldo (2016) and Pedersen et al. (2018)).

IMBs are installed by the Cold Regions Research and Engineering Laboratory (CRREL) to measure the ice mass balance of the Arctic sea ice cover (Richter-Menge et al., 2006; Perovich and Richter-Menge, 2006). Buoy components include acoustic sounders and a string of thermistors. The thermistor string is extending from the air, through the snow cover and sea ice, into the water with the temperature sensors located every 10 cm along the string. It measures the physical temperature with an accuracy of 0.1 K. **The acoustic sounder measures the position of snow and ice surfaces with a precision of 5 mm, from which the snow depth is computed.** The buoys also include instruments to measure air temperature, barometric air pressure and GPS geographical position (Perovich et al., 2017). Several IMBs are deployed by the CRREL at different locations and times during the year. We only use Arctic buoy data recorded during winter (December 1^{st} to April 1^{st}) to avoid cases where ice starts to melt. **The IMB available for this study are all located on MYI, with an ice thickness ≥ 1 meter.** A summary of buoy information corresponding to these criteria is given in Table 1 and the IMB locations are shown in Figure 1. IMB measurements collocated with AMSR2 TBs used in this study totalize 2845 observations.

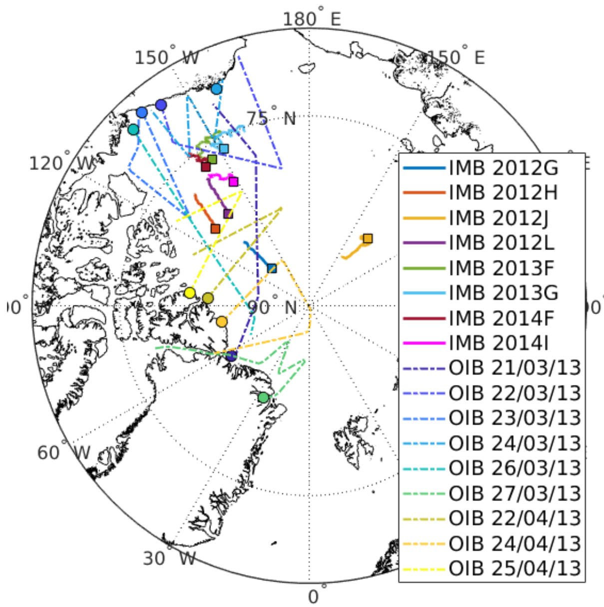

Figure 1. Ice Mass balance Buoy (IMB) and Operation Ice Bridge (OIB) flight locations over Arctic sea ice. Squares indicate the position of IMBs on December 1^{st} and circles indicate the starting points of OIB campaigns.

For snow depth retrieval, we also used data from the OIB airborne campaign. The NASA OIB project has collected ice and snow depth data in the Arctic during annual flight campaigns (March-May) since 2009. The data are especially valuable in this context since they contain snow depth information from the snow radar onboard the aircraft, not only from single points, but continuously along the flight path. **The vertical resolution of the OIB snow radar is 3 cm, and the uncertainty on the snow depth is around 6 cm compared with in situ measurements (Kurtz et al., 2013).** In the RRDP, the snow depth data from OIB snow radar are averaged into 50 km sections to be collocated with AMSR2 observations. For our study we use the OIB data from the 2013 campaign. **It totalizes 408 observations over 8 days in March and April and covers FYI and MYI areas.** Figure 1 summarizes the location of IMBs and OIB campaigns over the Arctic ocean.

It is important to note that there are discrepancies due to the scale, when comparing point measurements from buoys with the spatially averaged data from satellites or aircrafts (Dybkjær et al., 2012).

2.2 The database of simulated effective temperature and brightness temperature from sea ice properties

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 and Mätzler, 1999) described in Mätzler (2006). The simulations were part of an earlier version of the RRDP and the simulation methodology is described in Tonboe (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.

2.3 Methodology

In this study, we propose simple algorithms, using multilinear regressions, to derive the snow depth, the $T_{Snow-Ice}$, and the T_{eff} of sea ice from AMSR2 TBs.

The measurements from the IMB 2012G, 2012H, 2012J, and 2012L, collocated with AMSR2 TBs, are used as the training dataset for the different regressions to retrieve snow depth and $T_{Snow-Ice}$. These buoys have been selected because they are located in different regions across the Arctic and show a large range of snow depths. The measurements from IMB 2013F, 2013G, 2014F and 2014I which are all located in the Beaufort sea are used as the testing dataset.

First, the IMB snow depth is expressed as a function of the AMSR2 TBs using a multilinear regression (see Section 3.1). The OIB data are used for the forward selection and the IMB training dataset is used to perform the regression. Second, the $T_{Snow-Ice}$ is expressed as a function of TBs and snow depth, using linear regressions. An automated method to detect the position of the snow-ice interface on the vertical temperature profile measured by the IMB thermistor string is developed (see Section 4.1). Then, the IMB training dataset is used to perform the regressions (see Section 4.3). For this part there are two consecutive regressions: the first one is done between the centered (the average was subtracted) $T_{Snow-Ice}$ and TBs ; the second one is done between the $T_{Snow-Ice}$ corrected for the TB dependence and the snow depth. Third, the sea ice T_{eff} at different microwave frequencies is expressed as a function of the $T_{Snow-Ice}$ (see Section 5.2). This final step is using the simulations from a thermodynamical model and MEMLS to derive linear regression equations for the T_{eff} at frequencies between 6 and 89 GHz. The T_{eff} at 50 GHz is of special interest for atmospheric sounding applications.

3 Snow depth estimation

3.1 Multilinear regression to retrieve the snow depth

A forward selection method is used to choose the best AMSR2 channels to retrieve snow depth. It is a statistical method to determine the best predictor combinations (here, AMSR2 TBs) to retrieve a variable (here, snow depth). **We use the stepwise regression (Draper and Smith, 1998). It is a sequential predictor selection technique: at each step statistic tests are computed, and the predictors included in the model are adjusted.** Our training dataset for this forward selection is the OIB snow depth from the 2013 campaign included in the RRDP. OIB data are chosen for forward selection because the data cover a large area with a wide range of snow depths. In addition, the scale of the averaged OIB data is closer to satellite footprint than buoy measurements, increasing the consistency with the satellite observations. Forward selection tests have also been done with the IMB training dataset but the results were not satisfactory. We find that the best channel combination for snow depth retrieval is the combination of the 3 channels at 6.9, 18.7, and 36.5 GHz in vertical polarization (6V, 18V, and 36V).

Then, a multilinear regression is conducted using the IMB training dataset (buoys G, H, J, L in 2012 collocated with AMSR2 TBs). The snow depth is given as a linear combination of the TBs at 6V, 18V, and 36V :

$$SD = 1.7701 + 0.0175 \cdot TB_{6V} - 0.0280 \cdot TB_{18V} + 0.0041 \cdot TB_{36V}, \quad (2)$$

with SD the snow depth expressed in m and TB in K. This model was trained with snow depths between 5 and 40 cm.

The forward selection has also been tested constraining the number of predictors to 2 and 4. The combinations obtained are: 18V and 36V for 2 channels, and 6V, 18V, 36V, and 89V for 4 channels. Then, the multilinear regression has been performed using these combinations of 2 or 4 channels. The results show that the 3 channel combination is the best in terms of RMSE and correlation compared to the 2 or 4 channel combination (see Section 3.2).

3.2 Results of the snow depth retrieval

Figure 2 shows the comparison between the observed snow depth measured by the acoustic sounder of IMB and the regressed snow depth computed from AMSR2 TBs with Eq. 2. The RMSE between the IMB snow depth observations and our snow depth regression is 12.0 cm and the correlation coefficient is 0.66, **using the IMBs 2013F, 2013G, 2014F and 2014I (which are not in the training dataset).** The buoy 2013F observes a large snow depth (> 40 cm) which is outside the bounds of our snow depth model. Tests are conducted to improve the estimation, including the 2013F buoy in the training dataset, with equal numbers of observations for different ranges of snow depths: it does not improve the results. Our model obtained the same snow depth estimation between buoys 2013G and 2013F. It is consistent because these buoys are spatialy very close. Therefore, we suspect that the 2013F buoy is located **nearby a ridge or hummock** where the local snow depth is large but not detectable at the satellite footprint scale. Without including the buoy 2013F in the computation, the RMSE for our snow depth model is 5.1 cm and the correlation coefficient is 0.61.

We also compare the snow depth retrievals with the measurements of the 2013 OIB campaigns (see Figure 3) **with the ice type computed from the gradient ratio between 19 and 37 GHz (Baordo and Geer, 2015).** Our snow depth regression (Eq. 2) RMSE is 6.26 cm and the correlation coefficient with OIB observations is 0.87. Note that the uncertainties on OIB data for the 2013 campaigns are between 2 cm and 22 cm with a mean Standard Deviation (StD) of 11 cm **(OIB snow depth StD provided in the RRDP). Looking at Figure 3, our snow depth regression is applicable to both ice types. The RMSEs computed for MYI and FYI are respectively 7.2 cm and 3.9 cm, and the correlations are 0.71 and 0.03. The RMSE is smaller for FYI because the snow depth variability of FYI is also smaller. The low correlation obtained for FYI can come from the limited number of observations and because the snow depth variability observed is within the signal noise.**

Spatial scales are different when comparing satellite measurements or airborne campaign measurements with buoy measurements. Discrepancies can appear due to the spatial variability of the snow depth. It can explain that the correlation is higher

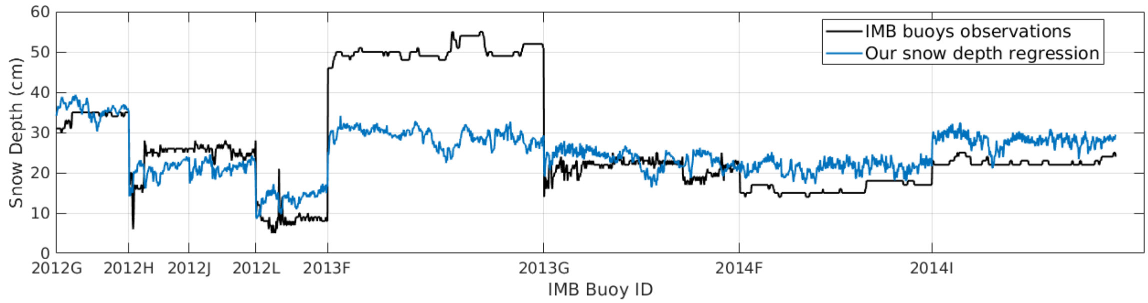

Figure 2. Time series of the comparison between snow depths from IMB observations and our multilinear regression (Eq. 2). The beginning of the measurements with a new IMB is indicated on the x-axis.

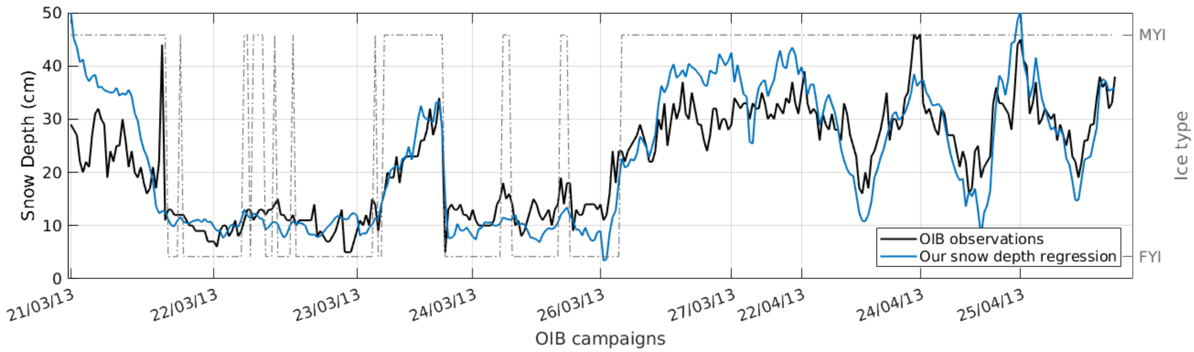

Figure 3. Time series of the comparison between snow depths (left y-axis) from OIB observations and our multilinear regression (Eq. 2). The beginning of the measurements with a new OIB campaign is indicated on the x-axis. For each measurement, the ice type is indicated in grey dashed line (right y-axis).

when comparing snow depth estimated from AMSR2 TBs with the snow depth observed from OIB radar. **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.**

4 Snow-ice interface temperature estimation

4.1 Automatic interface position detection

During winter, the air temperature is very cold meaning that the snow surface temperature is cold compared to ice and water temperatures. Through sea ice, the temperature profile is **piecewise linear** and temperature increases with depth (see Figure 4). In the air, the temperature gradient is small because of turbulent mixing. In the snow, the temperature gradient is larger

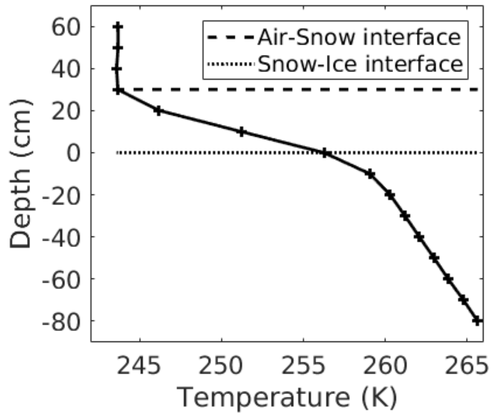

Figure 4. Averaged temperature profile (From December to February) measured by the IMB 2012G, with air-snow and snow-ice interface levels detected with our automated method.

due to the thermal properties of snow. Therefore, air-snow and snow-ice interface positions can be detected by changes in the temperature gradient. At the snow-air interface, the second derivative of the temperature profile reaches a maximum. At the snow-ice interface, the temperature gradient being lower in the ice than in the snow, the second derivative of the temperature profile reaches a minimum. Using these properties of the sea ice temperature profile, an automated method is implemented to detect the air-snow and the snow-ice interface positions in the temperature profile measured by the buoy thermistor string.

Figure 4 shows an averaged temperature profile through sea ice during winter, with the air-snow and snow-ice interface positions detected with our automated method. This method performs best during winter when the air is cold. It may not be applicable if the snow depth is lower than the vertical resolution of the thermistor string (10 cm), or if sea ice starts to melt and the temperature profile develops gradually toward an isothermal state. **The method selects the thermistor which is located the closest to the interface. Note that the real interface position can be located between two thermistors. Therefore, the shift between the real interface position and the thermistor the closest to the interface can be up to 5 cm. This can introduce uncertainties in our $T_{Snow-Ice}$ regression.**

4.2 Correlation between the brightness temperature and the snow-ice interface temperature

During winter, the vertical position of the snow-ice interface is fixed with respect to the buoy thermistor string. The thermistor string is frozen into the ice which means that the thermistor at the snow-ice interface will stay at that interface unless there is surface melt or snow ice formation and this rarely happens during winter. For each IMB, the snow-ice interface is detected with our automated method described in Section 4.1.

We use a correlation analysis to select the TBs at different frequencies describing the variability of the $T_{Snow-Ice}$. Figure 5 shows the correlation coefficient between $T_{Snow-Ice}$ and AMSR2 TBs computed using the data from all IMBs (Table 1). The 89 GHz TBs are highly correlated with the air temperature (R>0.75). The 18.7, 23.8 and the 36.5 GHz TBs have a low

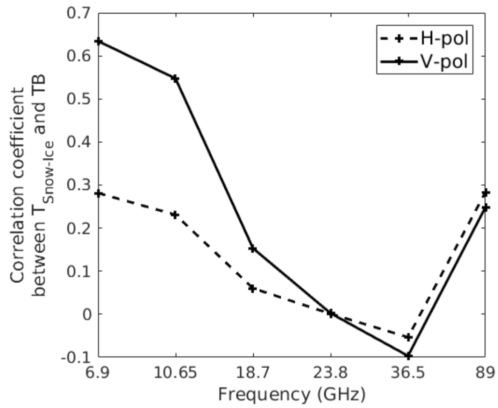

Figure 5. Correlation coefficient between the T$_{Snow-Ice}$ from IMBs and the AMSR2 TBs, as a funtion of AMSR2 frequency.

correlation with T$_{Snow-Ice}$ because of microwave scattering in the snow and/or shallow microwave penetration into the snow. The 7.3 GHz channel is ignored because it contains practically the same information as the 6.9 GHz channel. The TBs at 6.9 and 10.65 GHz at vertical polarization, have the highest correlation with T$_{Snow-Ice}$ (R>0.5). Therefore the 10.65 and the 6.9 GHz at vertical polarization (10V and 6V) channels are selected as inputs to the linear regression to retrieve the T$_{Snow-Ice}$.

4.3 Linear regressions to retrieve the snow-ice interface temperature

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 of the linear regression is unchanged:

$$\Delta T_{Snow-Ice} = a_1 \cdot \Delta TB_{6V or 10V} \Leftrightarrow T_{Snow-Ice} = a_1 \cdot TB_{6V or 10V} + offset_{buoy} \quad (3)$$

with $\Delta T_{Snow-Ice}$ and ΔTB describing the centered T$_{Snow-Ice}$ and TB. Figure 6 shows the linear regression between the T$_{Snow-Ice}$ and the TB at 6V and 10V, using the measurements from buoys 2012G, 2012H, 2012J, and 2012L. The slope coefficients (a_1) estimated between the T$_{Snow-Ice}$ and the TB at 6V and 10V are 1.086±0.020 and 1.078±0.019 respectively.

The offset ($offset_{buoy}$) in the linear regression equations between T$_{Snow-Ice}$ and the TB is different for each buoy, because it depends on the snow depth. The T$_{Snow-Ice}$ dependence on snow depth can be explained by the thermal insulation of snow (Maaß et al., 2013; Untersteiner, 1986). Here, we establish an empirical relationship between the T$_{Snow-Ice}$ corrected of the TB linear dependence at 10V or 6V, and the snow depth as follows:

$$T_{Snow-Ice} - a_1 \cdot TB_{10V\ or\ 6V} = a_2 \cdot f(SD) + a_3, \quad (4)$$

with $f(SD)$ a function of snow depth.

Three different linear regressions have been tested to relate the T$_{Snow-Ice}$ using: the snow depth directly, the inverse of the snow depth, and the logarithm of snow depth. Figure 7 shows the T$_{Snow-Ice}$ corrected from TB dependence as a function

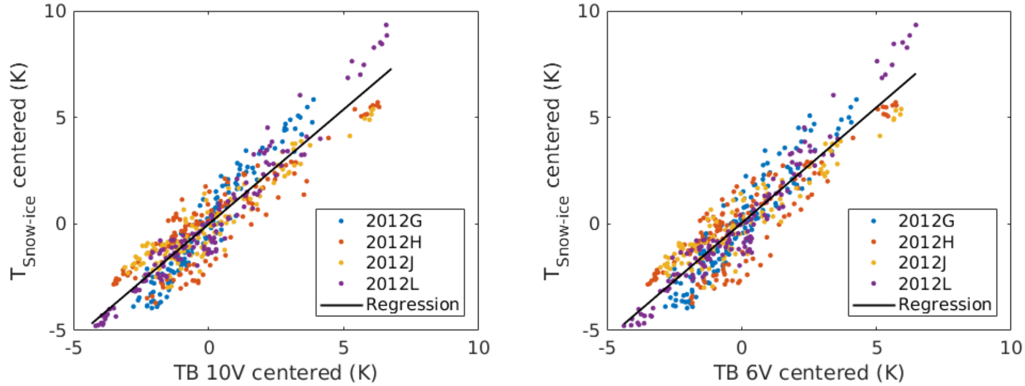

Figure 6. Centered $T_{Snow-Ice}$ expressed as a function of the centered TBs at 10V (left) and 6V (right). Data from the IMBs are in different colors depending on the buoy and the linear regression is the solid black line.

of snow depth. The different regressions are tested using the training dataset (IMB G, H, J, and L in 2012). The regression showing the best results uses the logarithm of the snow depth (solid black line in Fig. 7). The linear regression using the snow depth directly (red dashed line in Fig. 7) leads to an overestimation of the $T_{Snow-Ice}$ for large snow depth. The regression using the inverse of the snow depth (red dotted line in Fig. 7) leads to an underestimation for small snow depth. The RMSEs obtained on the $T_{Snow-Ice}$ are compared and the relation using the logarithm of snow depth shows the lowest RMSE. Based on these results, the final equations to relate the $T_{Snow-Ice}$ to the snow depth and the TB at 10V and at 6V are:

$$T_{Snow-Ice} = 1.078 \cdot TB_{10V} + 5.67 \cdot log(SD) - 5.13 \quad (5)$$

$$T_{Snow-Ice} = 1.086 \cdot TB_{6V} + 3.98 \cdot log(SD) - 10.70 \quad (6)$$

where $T_{Snow-Ice}$ and TB are expressed in K, and SD is expressed in m.

4.4 Results of the snow-ice interface temperature retrieval

Figure 8 shows the comparisons between the observed $T_{Snow-Ice}$ and the regressed $T_{Snow-Ice}$ using the 10V and 6V TBs (Eq. 5 and 6), and the *in situ* snow depth measured by the acoustic sounder of IMB. **The RMSEs are computed using the IMB 2013F, 2013G, 2014F, and 2014I.** The regression of the $T_{Snow-Ice}$ using the *in situ* snow depth with the 10V TBs (Eq. 5) is slightly better (RMSE = 1.78 K) than the regression with the 6V TBs (Eq. 6) (RMSE = 1.98 K). The variability due to the snow depth is better described with the regression using the 10V TBs. Figure 9 is the same as Figure 8 but with our snow depth estimation (Eq. 2). The RMSEs are 2.87 K for the 10V regression and 2.90 K for the 6V regression. The results are degraded because of the snow depth regression especially for the buoys with thick snow (~50 cm) or thin snow (~5 cm) (e.g., buoy 2013F and buoy 2012L). **Note that the regression is tested with IMBs which are all located on MYI. However, our**

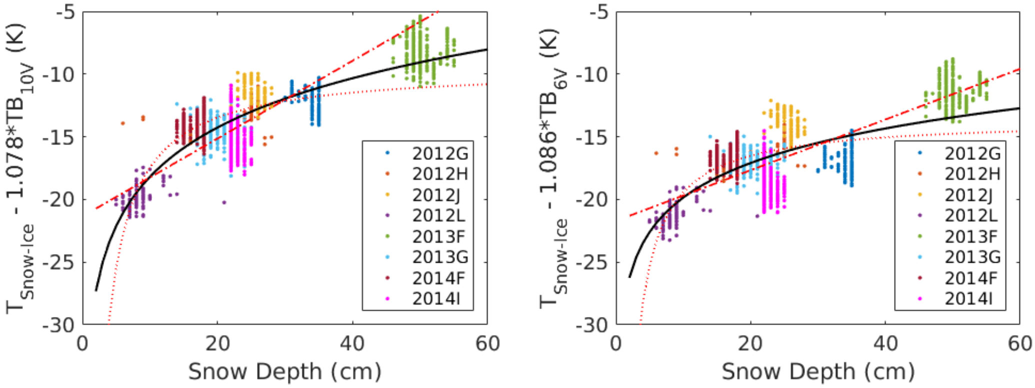

Figure 7. $T_{Snow-Ice}$ corrected of the 10V TB (left) and of the 6V TB (right) dependence as a function of snow depth. Data from the IMBs are represented by different colors, the regression using the snow depth is the dashed red line, the regression using the inverse of snow depth is the red dotted line, and the regression using the logarithm of the snow depth is the solid black line.

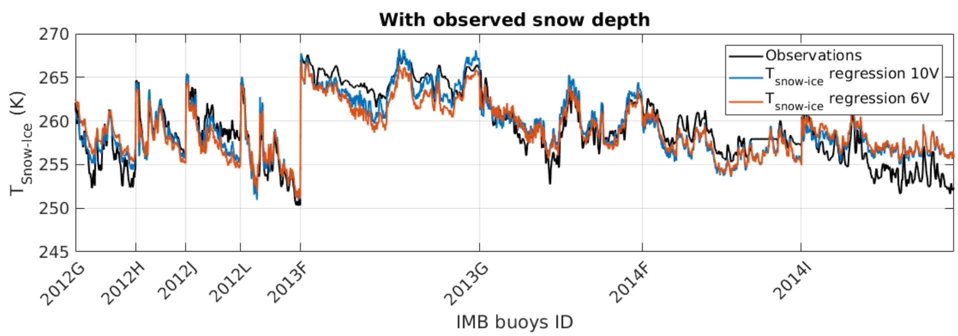

Figure 8. Time series of the comparisons between $T_{Snow-Ice}$ observations from IMBs (black line), and $T_{Snow-Ice}$ regressions with TBs at 10V (blue line) and at 6V (red line). The snow depth used in Eq. 5 and 6 is the snow depth observed by the IMB sounder. The beginning of the measurements with a new IMB is indicated on the x-axis.

algorithm to derive the $T_{Snow-Ice}$ is also applicable over FYI areas, as our snow depth algorithm is applicable to both ice types and our $T_{Snow-Ice}$ algorithm uses the channels 10V or 6V which are not sensitive to the ice type (Spreen et al., 2008).

5 Sea ice effective temperature estimation

5.1 Bias between the model and the observations

T_{eff} is related to the frequency and the incidence angle of the satellite 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

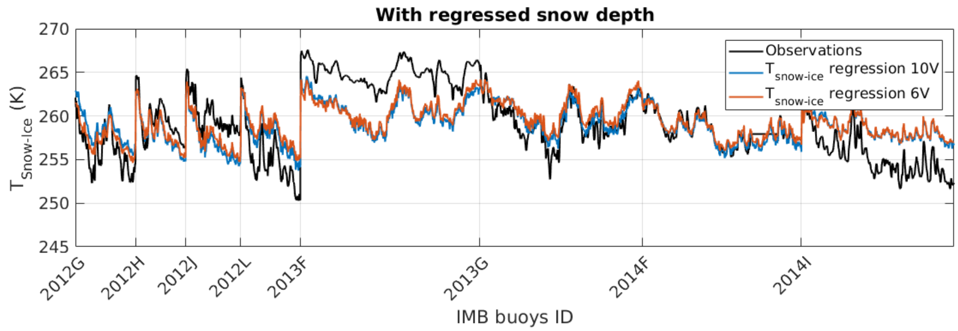

Figure 9. Same as Figure 8, using the regressed snow depth (Eq. 2) in place of in situ snow depth

T$_{effs}$ from the geophysical parameters. The T$_{eff}$ used here is available from a simulated dataset using a thermodynamical model and the microwave emission model MEMLS. The model set-up and the simulations are described in Tonboe (2010). **In this dataset, the TBs and the T$_{effs}$ are simulated using the T$_{Snow-Ice}$ and the input snow and ice profiles from the thermodynamical model.** Even though the simulated TB data are comparable to observations in terms of mean and standard deviation, both the thermodynamical model and the emission model are based on physical equations and are not tuned to observations. **TBs simulated with MEMLS are not fitted to AMSR2 TBs meaning that a bias is expected between the T$_{Snow-Ice}$ of the MEMLS simulated dataset (T$_{Snow-Ice\ MEMLS}$) and the T$_{Snow-Ice}$ estimated with our regression.**

The bias obtained is the mean value of the difference between the T$_{Snow-Ice\ MEMLS}$, and the T$_{Snow-Ice}$ regressed from Eq. 5 and 6 using the TBs of the MEMLS simulated dataset as inputs. Biases of 3.97 K and 4.01 K are estimated, for the regressions with 10V and 6V respectively. The RMSEs computed between the T$_{Snow-Ice\ MEMLS}$ and the T$_{Snow-Ice}$ regressed and corrected of the bias at 10V and 6V are 2.7 K and 2.07 K, respectively.

Figure 10 shows the T$_{Snow-Ice}$ from MEMLS simulated dataset as a function of TB at 10V and 6V, and the T$_{Snow-Ice}$ computed from our regressions (Eq. 5 and 6), with and without the bias correction. We can see that the slopes of our linear regressions are consistent with the data simulated from MEMLS.

5.2 Linear regression between the effective temperature and the snow-ice interface temperature

The T$_{eff}$ near 50 GHz in vertical polarization is correlated with the T$_{Snow-Ice}$ (Tonboe et al., 2011) and it can be expressed as a linear function of the T$_{Snow-Ice}$:

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot T_{Snow-Ice\ MEMLS} + b_{2(freq,pol)} \tag{7}$$

with T$_{eff}$, b_1 and b_2 depending on the frequency ($freq$) and on the polarization (pol). We use the MEMLS simulated dataset to calculate the linear regression between the T$_{Snow-Ice}$ and the T$_{eff}$ at 6.9, 10.65, 18.7, 23.8, 36.5, 50, and 89 GHz in vertical polarization. T$_{effs}$ at vertical and horizontal polarizations are about the same. Only the vertical polarization is considered here, because TBs measurements are noisier at horizontal polarization due to the variability of sea ice emissivity at this polarization.

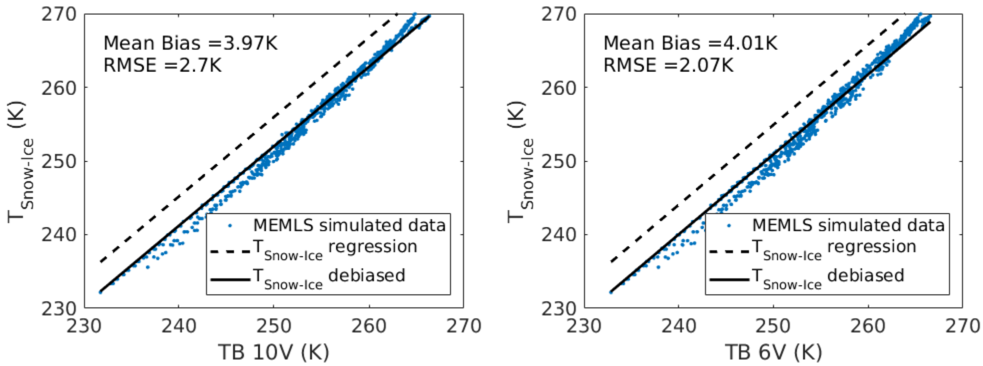

Figure 10. Comparisons between the $T_{Snow-Ice\ MEMLS}$ from the MEMLS simulated data in blue points, the regressed $T_{Snow-Ice}$ (Eq. 5 and 6) in dashed black line, and the regressed $T_{Snow-Ice}$ debiased to fit the MEMLS simulations in solid black line at 10V (left) and 6V (right) channels.

Figure 11 shows the T_{eff} at 50V as a function of $T_{Snow-Ice}$. The linear regressions between the $T_{Snow-Ice}$ and the T_{eff} at different frequencies are computed. **The coefficients b_1 and b_2 of Eq. 7 are given in Table 2.** The slope coefficient of the regression increases with frequency, meaning that the sensitivity of the T_{eff} to the $T_{Snow-Ice}$ is increasing with frequency between 6 and 89 GHz. 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 near to 1, meaning that the **penetration depth is close to the depth of the snow-ice interface.** The RMSEs are below 1 K, with the regression of T_{eff} at 50V showing the lowest RMSE (0.33 K), and at 89V showing the highest RMSE (0.92 K).

These linear regressions between the T_{eff} and the $T_{Snow-Ice\ MEMLS}$ (Eq. 7) are the final step to retrieve the T_{eff} of sea ice at microwave frequencies as a function of TBs, using the work in the previous sections to express the $T_{Snow-Ice}$ as a function of TBs (Eq. 2, and Eq. 5 or 6). The biases between the AMSR2 observations and the MEMLS simulated dataset are taken into account replacing $T_{Snow-Ice\ MEMLS}$ by $T_{Snow-Ice}$ estimated from AMSR2 TBs with a bias correction (see Table 2):

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 3.97) + b_{2(freq,pol)}, \text{ for the regression using 10V TB} \quad (8)$$

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 4.01) + b_{2(freq,pol)}, \text{ for the regression using 6V TB} \quad (9)$$

6 Discussion

For days in November, January, and April, Figure 12 shows the maps of the snow depth estimated with our multilinear regression (Eq. 2), the $T_{Snow-Ice}$ estimated with our multilinear regression (Eq. 5), and the MYI concentration products from the

Table 2. Regressions of the T_{eff} for different frequencies at vertical polarization as a function of the $T_{Snow-Ice}$ (see Eq. 7) using the MEMLS simulated dataset.

Frequency (GHz)	slope coefficient b_1	offset (K) b_2	RMSE (K)
6.9	0.888	30.2	0.89
10.7	0.901	26.6	0.75
18.7	0.920	21.5	0.63
23.8	0.932	18.4	0.57
36.5	0.960	10.9	0.41
50	0.989	2.96	0.33
89	1.06	-16.4	0.92

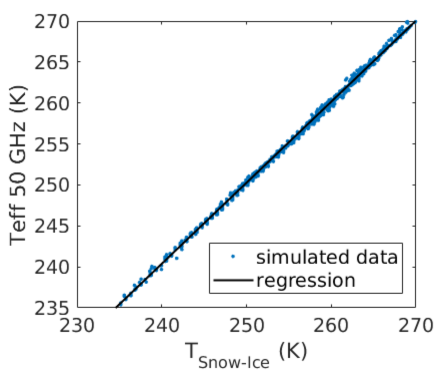

Figure 11. Regression of the T_{eff} as a function of $T_{Snow-Ice}$ at 50 GHz in vertical polarization. The data from the MEMLS simulations are in blue points and the linear regression is the solid black line.

University of Bremen (https://seaice.uni-bremen.de). To perform our regressions, we use the AMSR2 TBs (Level L1R) provided by JAXA and the SIC from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) data. Only the areas with 100% SIC are considered to compute the snow depth on sea ice and the $T_{Snow-Ice}$ with our method. Maps of the MYI concentration from University of Bremen are derived from AMSR2 and from the Advanced SCATterometer (ASCAT) with the method of Ye et al. (2016a, b).

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

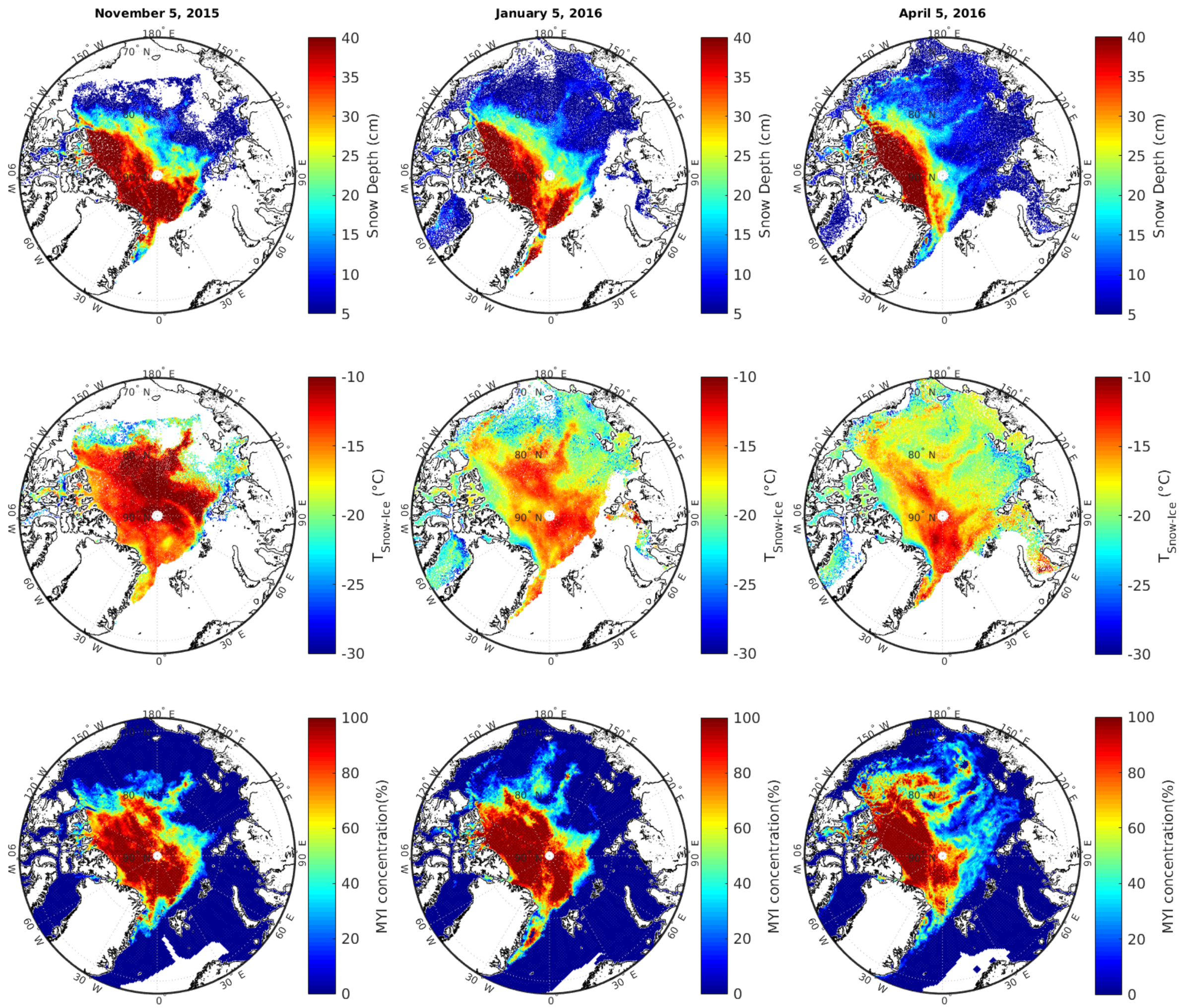

Figure 12. Maps of the snow depth (first row) and the $T_{Snow-Ice}$ (second row) estimated from our multilinear regression using AMSR2 TBs, with MultiYear Ice (MYI) concentration products (third row) from the University of Bremen on November 5, 2015 (left), January 5, 2016 (middle) and April 5, 2016 (right).

anticipated. **We can observe that the snow depth is larger in areas with larger MYI concentrations. The variability of the snow cover is low during winter, as the snow depth reaches a maximum by December and remains relatively unchanged until snowmelt (Sturm et al., 2002).**

For $T_{Snow-Ice}$, in January and April when the air temperature is cold (between -20 and -30°C over the whole Arctic, on January 5 and April 5, 2016 from ERA-Interim air temperature), the areas with large snow depth show larger $T_{Snow-Ice}$ because of the thermal insulation power of the snow. It is different in November: the air temperature is warmer ($\sim$ -5°C near

Kara sea, ∼ -15°C near Laptev sea and ∼ -25°C in central Arctic and Beaufort sea, on November 5, 2015 from ERA-Interim air temperature) and the areas with thinner snow show larger $T_{Snow-Ice}$ which are close to the air temperature (Perovich and Elder, 2001). Note that we can observe low $T_{Snow-Ice}$ in some locations near the sea ice margins due to the presence of open ocean in the satellite footprint. As the brightness temperature of open water is low, the total brightness temperature measured is decreased and it impacts our $T_{Snow-Ice}$ estimation.

Visually the $T_{Snow-Ice}$ shows a high correlation with the distribution patterns of multiyear ice concentration of the same days: the highest values are found in the north of Greenland and in the Canada Basin, with some branches of higher values extending from there towards the Siberian coast, marking the Beaufort gyre of the Arctic sea ice drift (see the animations for the same year at https://seaice.uni-bremen.de/multiyear-ice-concentration/animations/). The main differences between FYI and MYI are, on average, the higher thickness of MYI and its higher snow load. Both effects will influence the $T_{Snow-Ice}$. Under the same conditions, a higher ice thickness will lead to a lower $T_{Snow-Ice}$. In contrast, it will be higher if only the snow depth is increased. The positive correlation between MYI concentration and $T_{Snow-Ice}$ suggests that the influence of the higher snow depth on MYI outbalances that of the higher ice thickness on the $T_{Snow-Ice}$, emphasizing the important role of snow on sea ice in its thermodynamic balance.

The similar patterns observed between the maps of the $T_{Snow-Ice}$ and the MYI concentration on Figure 12 are encouraging and gives confidence in the methodology developed here, as these MYI concentration products are from **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).**

7 Conclusions

We derive simple algorithms to estimate sea ice parameters such as the snow depth, the $T_{Snow-Ice}$, and the T_{eff} of sea ice at microwave frequencies, from AMSR2 channels. This is achieved using the ESA RRDP which contains AMSR2 data collocated with IMB data and OIB campaign data. In addition, simulated TB outputs from a sea ice version of MEMLS are used for the regression of the T_{eff}. All the equations to retrieve these sea ice parameters are derived using several linear and multilinear regressions.

Our regression to retrieve the snow depth over winter Arctic sea ice uses the TBs at 6.9, 18.7 and 36.5 GHz in vertical polarization. **A RMSE of 5.1 cm is obtained between the estimated and the IMB snow depths using an independent IMB test dataset. This snow depth retrieval is applicable to FYI and MYI, with lower uncertainties for FYI than for MYI (3.9 cm compared to 7.2 cm)**. To retrieve the $T_{Snow-Ice}$, two relations are derived using two different AMSR2 channels (10V or 6V) and the estimated snow depth. The two regressions show similar results. **The errors 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 to FYI as the 6V and 10V channels are not sensitive to the ice type (Spreen et al., 2008).** Finally the T_{effs} at 6.9, 10.65, 18.7, 23.8, 36.5, 50, and 89 GHz in vertical polarization are retrieved as a function of $T_{Snow-Ice}$ using linear regressions. At the final step, the RMSEs of the linear regressions between the simulated $T_{Snow-Ice}$ and the T_{eff} for all channels are lower than 1 K, with a minimum value of 0.33 K at 50 GHz which is a key frequency for atmosphere temperature retrieval. The methodology to estimate snow depth and $T_{Snow-Ice}$ has been applied to several days during a winter season. It shows consistent results with MYI concentration estimates obtained independently.

These algorithms can be used to create snow depth and $T_{Snow-Ice}$ products which can improve the study of sea ice variability (e.g., sea ice growth). Informations on the $T_{Snow-Ice}$ may help in sea ice models by constraining the sea ice temperature gradient and the thermodynamical ice growth. The T_{eff} estimations can be used in atmospheric radiative transfer calculations and to reduce noise in SIC retrieval algorithms (Tonboe et al., 2013) (e.g., EUMETSAT OSISAF global SIC product).

Author contributions. This study was conducted by L.K. and supervised by R.T.T. and C.P.. G.H. contributed to the analysis and to the correction of the draft.

Competing interests. The authors declare no conflict of interest.

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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}):

$$TB = e_{eff} \cdot T_{eff} \tag{1}$$

"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 Tem- perature 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.

$$\Delta T_{Snow-Ice} = a_1 \cdot \Delta TB_{6Vor10V} \Leftrightarrow T_{Snow-Ice} = a_1 \cdot TB_{6Vor10V} + offset_{buoy} \quad (2)$$

with $\Delta T_{Snow-Ice}$ and ΔTB describing the centered $\mathbf{T}_{Snow-Ice}$ 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:

$$T_{snow-ice\ MEMLS} = Tsnow - ice - 3.97. \quad (3)$$

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

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

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

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

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)."

Response to reviewer 2

We thank the reviewer for his carefull reading of the manuscript and his numerous comments which significantly improved this paper.

Summary: A suite of linear regressions is derived consecutively to derive i) an estimate of snow depth, ii) an estimate of the snow-ice interface temperature and, finally, iii) of the effective temperature Teff - all from brightness temperature (TB) observations of the AMSR2 in the Arctic Ocean during winter time. This suite is developed with the aid of TB collocated with weather forecast data, OIB snow depth data and IMB snow depth and snow-ice interface temperature observations as well as with simulations of TB, snow-ice interface temperature and Teff with a thermodynamic model in combination with a microwave emission model. Observed and retrieved snow depths and snow-ice interface temperatures are compared by means of RMSD and correlation. Examples of retrievals of the Arctic-wide distribution of snow depth and snow-ice interface temperature are shown and discussed in the context of a multiyear ice concentration product. This paper is an interesting contribution to the scientific literature in this field. Before it could become acceptable for publication the authors need to take care of several issues which are required to understand their methodology, to potentially re-do their analysis, and to better underline the new aspects of their work in front of the background of work done by others. Solving most of these issues will help the authors to reply to my suggestions to improve their discussion of the results achieved. I therefore hand this manuscript back to the authors, asking for major revisions. The general and specific comments will potentially aid in this process.

General comments GC1: The introduction needs a better structure: Relevance - previ- ous work - shortcomings - what will you do and why. The introduction also requires an improved set of references to make clear the current state-of-the-art of snow-depth on sea ice retrieval and also snow-ice interface temperature retrieval.

The introduction has been rearranged with references added following the reviewer comments. Especially, a state of the art of snow depth algorithm, and more information about the sea ice emissivity and the ice type have been added.

GC2: The description and illustration of the methodology to retrieve the snow depth but also in particular the snow-ice interface temperature lacks important details for the understanding. See my specific comments with this regard.

More information about the stepwise regression for the snow depth has been added: "We use the stepwise regression (Draper, 1998). It is a sequential predictor selection technique: at each step statistic tests are computed, and the predictors included in the model are adjusted."

For Tsnow-ice, an equation with explanations has been added for the better understanding of the methodology.

"Thus, the temperature offset between the buoys is removed and the slope of the linear regression is unchanged:

$$\Delta T_{Snow-Ice} = a_1 \cdot \Delta TB_{6V or 10V} \Leftrightarrow T_{Snow-Ice} = a_1 \cdot TB_{6V or 10V} + offset_{buoy} \quad (1)$$

with $\Delta T_{Snow-Ice}$ and ΔTB describing the centered $\mathbf{T}_{Snow-Ice}$ and TB."

GC3: The title "promises" retrieval of effective temperature but the paper kind of stops before having applied a method retrieving it from TB data and discussing any results into this direction.

All the equations needed to retrieve the Teff from TBs are presented in the paper and a final equation has been added to highlight it.

"These linear regressions between the $\mathbf{T}_{eff}$ and the $\mathbf{T}_{Snow-Ice\ MEMLS}$ are the final step to retrieve the $\mathbf{T}_{eff}$ of sea ice at microwave frequencies as a function of TBs, using the work in the previous sections to express the $\mathbf{T}_{Snow-Ice}$ as a function of TBs. The biases between the AMSR2 observations and the MEMLS simulated dataset are taken into account replacing $\mathbf{T}_{Snow-Ice\ MEMLS}$ by $\mathbf{T}_{Snow-Ice}$ estimated from AMSR2 TBs with a bias correction (see Table 2):

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 3.97) + b_{2(freq,pol)}, \quad (2)$$

for the regression using 10V TB.

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 4.01) + b_{2(freq,pol)}, \tag{3}$$

for the regression using 6V TB."

GC4: I am a bit lost with regard to a critical discussion of the results. - I neither found a discussion about how accurate the automatically retrieved snow-ice interface temperatures are, nor did I find a discussion about the dependency of the different retrievals on the same data. For instance: The fact that in Figure 12 snow depth and multiyear ice concentration have a certain degree of correlation can partly be explained by using the same frequencies and polarizations (see eq 1 and the microwave data entering the MYI concentration maps). The same applies to Tsnow-ice, which is via its correction with the snow depth is also related to these frequencies. - Uncertainty estimates are missing in any of the retrievals presented. - A critical discussion about the physics behind the many linear regressions used would definitely add to the understanding of the paper and would give the approach more credibility.

A discussion between the dependency of the retrieval of MYI and our retrievals has been added. Our retrievals have been systematically tested and compared with observations from IMB and/or OIB campaigns (see Figures 2 and 3 with section 3.2 for the snow depth retrieval and Figures 8 and 9 with section 4.4 for the snow-ice interface temperature). The errors on the snow depth and the snow ice interface temperature retrievals are mentionned also in the abstract and in the conclusion of the paper.

Specific comments P2, L4-5: "Improved estimates of ... from satellite observations ..." implies that such estimates exist already. But they have not been mentioned yet. P2, L8-19: I find this paragraph relatively weak and not suitable yet for this introduction.An improved paragraph would - more clearly separate between snow deoth and Tsnow-ice retrieval - find more references for both these parameters. Comiso et al (2003) forinstance also refer to Tsnow-ice; there are other papers dealing with the applicationand evaluation of the Markus and Cavalieri (1998) (MandC98) approach in the Arctic;there are other papers discussing about the caveats of the MandC98 and suggesting improved retrieval, e.g. Markus et al., 2011; Kern and Ozsoy-Cicek, 2016. Isn't there a paper by Rostosky et al., 2018, also, where an alternative approach is proposed. Finally, there have been various conference contributions (Frost et al., various years)which results possibly should not remain to be unmentioned here. All these, in my eyes, belong to the introduction. Here you motivate why you think that you approach brings added value to the research landscape in this topic. - The RRDP data set is a co-production of ESA and EU (SPICES project) activities and this needs to be mentioned. Also, to my knowledge, this data set has been published and is citable with a doi. You might want to ask Leif Toudal Pedersen about this. - It should be mentioned that routinely processed data sets of snow depth and snow-ice interface temperature exist. It makes sense to not only check out the NSIDC data holding but also activites at JAXA and other institutions (metno for instance).

Several references have been added to better describe the algorithm state of the art. References to the RRDP has been added.

P2, L26/27: I guess it would not hurt to at least mention the substantial emissivity differences between first-year ice and multiyear ice here, i.e. the sensitivity to ice type. Discussions about FYI and MYI have been added throughout the text. P2, L31: On the one hand the "relationship ... is complicated at microwave frequencies > 18GHz" ... on the other hand "from 6 to 50 GHz [i.e. including those complicated frequencies] there is a high correlation between Teff and Tsnow-ice" This is a bit con- fusing and should be reformulated. Also the following statement that by "using linear regression" Teff can be estimated contradicts the previous mentioning of a complicated relationship.

It is the physical understanding which is complicated. The linear regression allows to derive the Teff at the first order.

P3, L12-15: - Please provide information about the product level which is used in this product and also detaiil whether swath data or gridded data are used. - For the co- location with the IMB as well as the OIB data sets it is important to know the search radius in space and time within which an IMB or OIB measurement is co-located with a satellite measurement.

L1R AMSR2 products are used and it is swath data. For the details see the RRDP documentation.

P3, L15: See one of my previous comments. There should be a DOI and citable reference.

The reference and doi have been added.

P3, L16-25: - 10 cm vertical resolution of the temperature measurements sounds a bit coarse. Please check whether there are not other (finer) vertical resolutions in different media. - How does the acoustic sounder penetrate the snow to measure the location of the snow-ice interface at 5 mm accuracy. So far I thought that these IMBs have an acoustic sounder looking downward to measure the position of the snow surface relative to the sounder and an acoustic sounder underneath the sea ice looking upwards, measuring the position of the ice underside; both together provides the total (sea ice + snow) thickness. The temperature measurements in the snow and sea ice are then used to figure out where (approximately) the snow-ice interface is located. - How are IMB measurements co-located? What is the sampling frequency? Was there any averaging performed?

The vertical resolution of the temperature measurements is 10 cm, and there are two acoustic sounders: one above and one below the sea ice (See http://imb-crrel-dartmouth.org/imb/ and 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.). Please see the reference to the RDDP documentation for more technical details.

P3, L26-31: - Please provide references about the OIB data and/or the OIB campaign. - The 408 observations ... are these the 50 km sections? Do these overlap or are these consecutive sections? - Why did you use data from 2013 only? - You give precision / accuracy estimates for the IMBs but not for the OIB data. Please provide such as well for OIB.

Yes, the 408 observations are the 50 km section data that are provided in the RRDP. The vertical resolution of the OIB snow radar is around 3cm and the uncertainty on the snow depth is around 6 cm (Kurtz et al., 2013).

P3, L33: "neither interpolated or smoothed ..." okay. What is the sampling in time? The IMB provides measurements every 1-2h.

The paragraph has been modified.

P4, Table 1: - What is the mean snow depth and ice thickness given in the last two columns? Is this an average over the entire time period the buoys lived ... or over the time period from which you used the data ... or are these the initial depth and thicknessvalues at buoy deployment? Please be more specific. - The time periods given in thesecond column do not last from Dec. 1 to Apr. 1. Why?

Mean snow depth and ice thickness is an average over the period specified in Table 1. This information has been added to the Table legend. The time period do not last for each buoy the Apr 1., because the buoys have been removed by the CRREL before.

P4, L1-2: I don't understand what you want to say with this sentence. I do not rate a difference of 1-4 K over 100km as a particularly good example to state something about how variable data from adjacent buoys could be.

The paragraph has been rewritten and shortened.

P5, L2-5: This is a very short description. What are the skills and limitations of this model to simulate TBs and Teff for snow-covered sea ice? Can the model deal with liquid water in the snow and/or with melt-refreeze cycles? For which microwave fre- quencies and polarization the model can be applied? What are the input atmospheric data? Even though the simulations were part of an earlier study it would be very helpful to have some key elements listed here.

Informations about the model have been added:

"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, 1999) described in Matzler, 2006. The simulations were part of an earlier version of the RRDP and the simulation methodology is described in Tonboe, 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."

P5, L13-19: This summary part is not very clear. - What is "forward selection"? - IMB snow depth is expressed as a function of TB using multilinear regression. ... then the IMB training data set is used to perform the regression ... ??? - "centred (avarage was subtracted)" -> I don't understand this. Centred between what? Which average was substracted? - What TB dependence are the TSnow-ice values corrected for? - Which snow depth data set is used here? The IMB training one? - Perhaps a schematic illustration with the data flow and the different regression steps would ease understanding of your method.

This is further explained in the respective sections of the paper and the references to the sections have been added.

P5, L25 to P6, L6: - Please explain why you use the OIB product with the much better spatial coverage and hence representation of the satellite footprint conditions only for the forward selection. Would it have been more straightforward and logical to carry out both, the forward selection AND the regression using the OIB data? What is the added value using the IMB snow depth values? - Please provide an additional table in which the results of the statistical forward selection are summarized. - Please explain the statistical measures used in the forward selection. May I ask whether you tried all frequency and polarization combinations? How many in total did you try? - Please provide at least an example, e.g. a scatterplot or 2-dimensional histogram, in which you illustrate the relationship between the 3 channels used for the best retrieval and the OIB snow depth data. It would be very intriguing to see how much the measurements scatter around the regression lines.

We want our snow depth algorithm to be optimized for IMB measurements. The IMBs also measure the Tsnow-ice which is one of our interest variable and the Teff is derived from the Tsnow-ice. So the OIB data were chosen for the forward selection only because the forward selection was not satisfactory with the IMB data as the snow depth variability is limited.

It is a stepwise forward selection. To select the most relevant AMSR2 channels, the stepwise regression (Draper,N. R., and H. Smith. Applied Regression Analysis. Hoboken. NJ: Wiley-Interscience,1998. pp. 307-312.) was used. It is a sequential parameter selection technique designed specifically for least-squares fitting. The method begins with an initial model, at each step p-value are computed and predictors included in the model are adjusted. We can constrain the number of predictors (here AMSR2 Tbs at different channels) to as many as we want.

P6, L7-12: - It is not entirely clear what were the input and the test data sets for these additional tests of the regression. Please be more specific about what you did. This goes back to the a schematic illustration which is missing. - How does the multi-linear regression work? Is it a stepwise linear regression? If not, how do you / the method assures that with the choosen parameter combination you end up in a minimum of the multi-dimensional RMSE "surface" (optimal parameter combination)? - Is there any uncertainty involved in your parameter estimation? Or, in other words, what is the uncertainty of the SD retrieved with equation (1) based on the multilinear regression?

It is exactly the same method as used previously (description P5 L25 to P6 L6). We use a stepwise regression to select the channels. The coefficient of the multilinear regression are then computed using a linear fit function with the least square method. The uncertainties given by the regression method itself are small compared to the error given by the comparisons with in-situ data.

P6, L14-20: - "snow depth estimate from MandC98" -> Did you compute this on your own? If yes, with which coefficients? If not, where did you take the snow depth infor- mation from? Without more detailed information about this it is not possible to properly evaluate the quality of your results. - What is the basis (in terms of time) for the intercomparison presented in this and the following paragraph? Are we talking about a 4-month average value?

Yes, I computed the snow depth using the AMSR2 Tbs at 19V and 37V following the equations/coefficients described in Markus and Cavalieri, 1998. The comparisons are done with the IMB data over the period given in Table 1.

P6, L21-27: - What do we know about the limitations of the MandC98 approach in terms of snow depth? - In L23/24 you kind of contradict your statement from L19/20. Please check. - I doubt that this particular buoy is located ON a ridge or hummock. In that case the local snow depth would probably not be very large because it can be expected that the wind blows the snow off the ridge and hummock. Maybe you wanted to write "nearby a ridge or hummock"? In that case your statement would be making more sense, I guess. Please check your hypothesis. - What happens with RMSE and correlation for MandC98 when skipping the data from 2013F? Please provide.

Yes, it is nearby a ridge or hummock. When skipping the 2013F, the RMSE increases for the MandC98. We removed MandC98 comparison. MandC98 is not designed for Arctic. It was here as a reference for the comparison but we do not want to evaluate it.

P6, L28 until P7, L2: - "uncertainties on OIB data" -> could you be a bit more specific what you mean here? How did you derive the uncertainties of the OIB data? Are these included in the product? Or are you referring to the difference between the satellite snow depth retrievals and the OIB data? - In this paragraph, as well as in the previous one and in Table 2 you are using the RMSE. In Figures 2 & 3 one can see that the difference between the IMB or OIB data on the one hand and the satellite data on the other hand can be quite large and therefore determine the RMSE. Did you try to compute an unbiased RMSE as well, by first subtracting the bias and then computing the RMSE? It might be worth a try. - The IMB data contain timeseries of snow depth which is derived from a relatively precise measurement of the location of the snow surface relative to the sounder (the downward looking acoustic sounder) and a relatively imprecise measurement of the ice-snow interface location by a temperature gradient method (to be described later in this paper apparently). Did you check the snow depth estimated from these two kinds of IMB measurements with the other data in the RRDP data set: precipitation (amount and type?) from ERA-Interim? It might be worth to do that to get a better feeling and the quality of the IMB snow depth data time series. - "Spatial scales are different" ... "the correlation is higher ..." -> yes, indeed the scales are different. You could attempt to plot a typical satellite footprint and then, try to overplot in scale a typical OIB measurement and a typical acoustic sounder footprint. If you cannot visualize it, then it might help to quantify the difference scales again in this sentence. Another important thing which needs to be taken into account when understanding the statistics of the different data sets used is the temporal sampling which is yet not mentioned for the IMB data and which you did not specify further for the OIB data. One could argue that it is not the pure difference in spatial resolution but also and in particular the vast difference in single observations entering the one value compared between IMB, OIB and satellite data.

The OIB uncertainties are included in the product and we added the reference. As we can see in Figures 2 and 3 there is not a typical bias between our regression and the IMB or OIB measurements so the results will be very close. The IMB snow depth is computed from the acoustic sounder measurements of the snow surface position and the ice surface position (and not with the snow-ice interface algorithm).

Table 2: - I suggest that you add the mean snow depth values as well as the standard deviation of the respective data set. The latter helps to figure out whether the data sets compared have a comparable statistics. - Am I correct assuming that the data shown in this table are only containing those IMB data which you did NOT use for the training of the method? If not that you could perhaps consider to leave these out and redo the computation. In any case it would be important to mention in the caption of the table data from which IMBs are included here.

Table 2 has been removed and the RMSEs have been computed using the IMB which are not from the training dataset.

Figure 2: - Is the length of the time series at the same scale for all IMBs? - You are also presenting the comparisong between the satellite data and the IMBs for the training data set. Is this done on purpose? -

The box in the top right, annotating the figure, should be placed outside to see the full range of MandC98 snow depths. - In any case Figure 2 contains a lot information for discussion. For instance: There is not much varition in IMB snow depth for all 4 IMBs except a small step change for 2012G and a large step change for 2012H. While for 2012G both CandM98 and your approack agree with each other perfectly well, both show a clearly increasing snow depth for the other 3 IMBs, CandM98 more than your approach, an increase which in this form is not confirmed by the IMBs. - For 2013F, 2014D and 2004I your approach looks like an amplitude-dampened version of MandC98. Most of the ups and downs in the Mandc98 time series are also present in your snow depth time series. What do you think causes the fact that the amplitude in short-terms (possibly unwanted snow depth variability) is so much smaller for your approach compared to that of MandC98? - How realistic do you think are step changes in IMB snow depth of 5 cm snow depth DECREASE as observed for 2013F and 2013G?

The time scale is the same for all IMBs, and it follows the description from Table 1. Our snow depth algorithm uses the 6V TB in addition to the 19V and 37V used in MandC98. The 6V TB is less sensitive to sea ice variability , than 19V and 37V Tbs. This is why our amplitude is reduced compare to MandC98. We decided to not show the MandC98 algorithm anymore in this section and to only focus on our algorithm. We also added a discussion about the ice type.

Figure 3: - While I doubt that an additional scatterplot with regression lines superposed does make sense for the IMB data sets I strongly recommend to add such kind of a figure here. For that it would be very good to obtain an estimate of the OIB snow depth retrieval uncertainty from the RRDP people and to estimate and uncertainty of both the MandC98 data and your approach, based on the uncertainties of the input data. Such a figure would add substantial value to the time series shown in Figure 3. - It might make sense to indicate in Figure 3 where data are over first-year ice and where over multiyear ice. - Important for Figure 2 and Figure 3 and in general all results which include MandC98 data is more information about how you used this data, i.e. whether you computed the snow depths on your own, whether you applied filters and if yes which, or whether you simply took the data out of a data base. This is important because in the products issued by NSIDC there are certain flags which, for instance flag multiyear ice because the MandC98 retrieval does not work properly there.

Yes, we added the ice type information on Figure 3 and the MandC98 algorithm has been removed.

P7, L5 until P8, L4: - "nearly piecewise linear" sounds strange. I suggest to either write "nearly linear" or "piecewise linear". Any complicated curved profile one can approximate piecewise linear. I am not sure that this is what you wanted to express here. - "because of turbulent mixing" -> well, ok, but what if this is not existent? Then you have a strong air temperature gradient near the surface. - Is the gradient of 35K/m a typical value for the temperature gradient in snow? If so - do you have a reference? If not, then it might make sense to specify this a bit more here. Otherwise you might make the wrong assumptions in the subsequent analysis.

Ok piecewise linear. We can work on a profile averaged over several measurements to avoid complication with the atmosphere. We suppressed the 35K/m. It was estimated just from one profile and it is not general.

P8, L5-8 / Figure 4: - Only 2 of the IMBs you used show an average snow depth subtantially larger than 20-25 cm, i.e. in only two of the IMBs temperature profiles you will have more than just 2 or 3 locations where the temperature is sampled. This does not sound a very safe method. - Figure 4 places the measurement locations exactly at the air-snow and ice-snow interfaces. I doubt that this is the case in reality. Please comment on that in the text - Figure 4 also reveals that the air-snow interface can be located quite accurately - at least in the shown setting - because the gradient change at this interface is indeed quite large. At the snow-ice interface however, the change in gradient is much smaller and almost not detectable - at least the way you plotted Figure 4. In other words, Figure 4 is not ideal to support / illustrate your method to derive the snow-ice interface from the IMB temperature profile data. See also my comment to Figure 5. - "if sea ice starts to melt" -> The isothermal state is something which is reached well after surface melt has commenced, am I right? It is hence first the temperature profile in the snow which changes before there is an isothermal state in the sea ice to be expected.

We know that it is not the real interface position. It is the air-snow and snow-ice interface level detected with our method as described in the Figure 4 legend. It correspond to the thermistor string level which is the closer to the snow-ice or air-snow interface. We added:

"The method selects the thermistor which is located the closest to the interface. Note that the real interface position can be located between two thermistors. Therefore, the shift between the real interface position and the thermistor the closest to the interface can be up to 5 cm."

P9, L2-5: - "thermistor at the snow-ice interface" -> Please provide this detail - if confirmed by references - in the data section. It is an important detail. - "detected with our automated method" -> Did you also evaluate the success / skill of this method and can you provide a measure of its uncertainty? I'd say it is essential to know this because the high precision with which the acoustic sounder measures the location of the snow surface of 5 mm is kind of useless without knowing what the potential bias of your method to locate the ice-snow interface is. Looking at Figure 4 and the description of your method it is certainly fair to assume that a bias of 5 cm might not be uncommon.

The acoustic sounder is used for the snow depth estimation. Here we only work on the thermistor string of IMB, and we need to know which thermistor is the closest to the interface. The vertical resolution of the IMB thermistor string is 10 cm, so the shift between the thermistor which is the closest to the interface and the real position of the interface can be of 5cm.

P9, L6-12: - 89GHz TBs are highly correlated with the air-temperature -> you don't show this in any of the figures, am I right? What is this statement for? Does it add value and is it relevant for the outcome of the paper? If relevant - How well are TBs of the other frequencies correlated with the air temperature? - Yes, at 18.7 to 36.5 GHz there might be some scattering of microwave radiation in the snow. Actually it differs between 18.7 GHz and 36.5 GHz that much that it form the basis for the snow depth retrieval of the MandC98 approach. Did you know that? I would therefore - par- ticularly because one can properly derive snow depths up to 40-50 cm depth not say that at these frequencies one has shallow penetration into the snow. I'd rather state that for all but one of your IMB penetration at these frequencies is deep enough to properly retrieve the snow depth. I suggest to reformulate this sentence therefore to avoid contradiction and misunderstandings. - "7.3 GHz is ignored" -> but you show it in Figure 5 nevertheless. Why? - Please try to provide an explanation why the horizon- tally polarized channels at 7 and 11GHz have a substantially lower correlation with Tsnow-ice. - It is more than likely that at these two frequencies (7 and 11 GHz) there is also substantial penetration into the sea ice - particularly if the underlying sea ice is multiyear ice and therefore has a close to zero salinity in its uppermost centimeters to a few decameters. Actually, taking Figure 4 and 5 together suggests that what you retrieve as the ice-snow interface temperature Tsnow-ice is not necessarily exact that temperature but rather a temperature of a sea ice layer underneath - that sea ice layer into which these two low frequency channel data penetrate. -> Temperature of the effective emitting layer.

Here we are looking for the most relevant channels to retrieve the Tsnow-ice. We want to explain why certain channels are not used and how we selected the 6V and 10V channels. We know that the scattering is different between 18 and 37 GHz and that there is penetration into the sea ice at 6.9 Ghz and 10.6 GHz. The point here is to choose the most relevant channels. The 7.3 GHz has been removed from Figure 5.

P9, L14-19: - If I understand your concept of "centred data" correctly then what you basically do is working with anomalies and compute the linear regression between the anomalies of Tsnow-ice and anomalies of the TBs at the two frequencies selected. How valid / representative is in this case your correlation analysis which you based on the absolute values and not on the anomalies. Wouldn't it have been more straightforward to carry out the correlation analysis with the data you will use at the end for your retrieval?

Yes, these are anomalies. An equation has been added to explain this.

$$\Delta T_{Snow-Ice} = a_1 \cdot \Delta TB_{6V or 10V} \Leftrightarrow T_{Snow-Ice} = a_1 \cdot TB_{6V or 10V} + offset_{buoy} \quad (4)$$

with $\Delta T_{Snow-Ice}$ and ΔTB describing the centered $\mathbf{T}_{Snow-Ice}$ and TB.

P9, L20/21: - I agree about the dependency of Tsnow-ice on snow depth. I do not understand, however, why you can assume that only the offset of the linear regression changes while the slope is the same for each IMB. If I take Figure 6 and draw a lin- ear regression for each of the four IMBs used I will get different offsets AND different slopes. Please explain. - Maass et al. (2013) is a reference which certainly cites itself older references about the mentioned isolating effect of snow. Could be that the book by Untersteiner is a more appropriate reference here. - Finally: Do we expect a linear relationship?

You will certainly get different offsets and different slopes. We do not want to developp an algorithm for each buoy. We have developed a relationship which applies more generally. The references have been added.

Equation 2: I suggest to set up this equation in the same fashion as equation 3. The way done currently is confusing. I would stick with the notation that Tsnow-ice has the form ax + b + c where ax + b are originating from the linear regressions shown in Figure 6 and c is the correction faction based on the snow depth. That you are showing the content of Eq. (2) in Figure 7 is a different thing. In equations (2),(3) and (4), the brightness temperature at 10V and 6V are used. To obtain this expression a first step was to use the centered TBs 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 to derive the final equation.

We added an equation to make this clearer (see comments above).

P10, L5-16 / Figure 7: - When I look at Figure 7 I do not necessarily "buy" that using the inverse SD leads to an underestimation of small snow depths. I would say that the majority of data pairs of IMB 2012L fits better to the 1/SD than to the log(SD) curve. The same could be said for 2013F and the SD curve. I suggest to first remove outliers and then compute the RMSD between the fitting curve and the SD values for each IMB for each of the three fits used to have a more objective measure of the skills of the fits. These values can easily be compiled in a Table. - By the same token I recommend to discuss the physical background using these different fits. Is there perhaps evidence that one of these is particularly suitable given what we know about the interaction of microwave radiation and snow on sea ice as well as about the relationship between microwave radiation, penetration depth and Tsnow-ice? - I would highlight in the caption of Figure 7 and once more in the text that IMBs from 2012 serve as training data and that IMB data from 2013 and 2014 are independent and serve as kind of a quality check of the fits shown in Figure 7. You might even want to highlight this by choosing either different symbols or different symbol sizes. - Finally, I guess you need to explain in a bit more detail how you switch from the linear regressions given on Page 9, Lines 18/19 to equation 2 and 3 because of three (addition to my comment farther up about why only the offset changes) reasons. 1) What happens to the offset of 0.020 and 0.019? 2) The regressions obtained from Figure 6 are computed using the TB and Tsnow-ice anomalies. If I am not mistaken, you need to use the TB anomalies in Equations 2 and 3 as well then ... this is not clear. It is particularly not clear whether the Tsnow-ice value obtained with equations 3 and 4 is just the anomaly or the "absolute" value and if the latter, where is the switch where you step back from anomaly to absolute value? 3) The snow depth you are using here ... is this the one you obtained yourself with Eq. 1 or is this (has this to be) an independent, externally provided snow depth? If it is the snow depth from Eq. 1 then at least Eq. 4 are not independent as both contain in some way information of the 6 GHz channel. See also comments above for the different regression step and the switch from TB anomalies to Tbs.

Snow and sea ice physics are complicated and we have chosen to use an empirical model because the RRDP development made this possible. Unfortunately, the dataset is still limited. The regressions with different functions (linear, inverse, or logarithm) are very close, but we can see that the logarithmic function is the best compromise. In the future, this could be re-computed with a larger database of snow depths. The snow depth used here is the in situ snow depth provided by the IMB.

P10, L18 until P11, L7 / Figure 8 + 9: - Figure 8 and 9 only partly answer my point (3) farther up whether you need an independent (external) snow depth estimate or you can use the one retrieved with your method. - I guess it is important to discuss Figure 8 and 9 in detail. Figure 8 uses the IMB observed (or better derived) snow depth. The agreement between computed and observed (better estimated) Tsnow-ice is certainly better than in Figure 9. This needs to be stated - potentiall also in form of mean differences and standard deviations in a separate table. - I cannot see in Fig. 8 that 2012L is particularly bad. It is actually together with 2012H the IMB with the best agreement. 2012G has a positve bias (Tsnow-ice retrieved > Tsnow-ice "observed"), 2012J a negative one. 2013F and 2014F both have a negative bias while 2013G and especially 2014I have a positive bias. Is this reflected by Figure 7? - Please remain critical. Do you believe in the decrease in IMB Tsnow-ice for 2014I to -20degC until the end of the period at a mean snow depth of > 20 cm? - Is the difference between Figure 8 and 9 for 2013F and 2014I in line with the differences in retrieved snow depth versus IMB snow depth? The negative (2013F) and positive (2014I) biases become larger when going from Fig. 8 to 9. Hence the regressed snow depth has to be larger than IMB snow depth for 2013F and smaller than IMB snow depth for 2014I. Is this the case? - Since IMB snow depth estimation requires IMB Tsnow-ice, these two quantities are not independent. How useful is it then, to compare a remote sensing product which uses IMB snow depth (as a function of IMB Tsnow-ice) with the IMB Tsnow-ice itself?

The decrease of 20degC with 2014I IMB is measured by the thermistor of the buoy. Tsnow-ice increases with snow depth (see equations 3 and 4). The negative bias for 2013F is because the snow depth estimated from satellite measurements is underestimated compared to in situ measurements at the buoy location, because of local conditions. Same for the overestimation for 2012L buoy.

P12, L3-8: - What is the ultimate goal to compare model results, which are seemingly completely independent of the observations in terms of ice type, snow depth /accumu- lation, and time period used (?), with your estimations of Tsnow-ice. Please provide 1-2 introductory sentences. Otherwise it pretty much sounds like comparing apples with oranges.

We added: "The Teff is related to the frequency and the incidence angle of remote 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 Teff from the geophysical parameters."

P12, L9-12: - Please use the same number of digits: 2.7 K and 2.1K instead of 2.07K. - The bias-corrected regressed Tsnow-ice values show a larger difference between 10V and 6V than found in the previous section. Why? What could be the reason? Is it because the model is capable to handle the relationship between the frequency- dependent penetration depth into the sea ice underneath the snow-ice interface and Tsnow-ice better than your estimations based on IMB-data based estimates of Tsnow- ice and its correlation with the TBs at the respective frequencies? (See my comment to figure 5).

The change has been done.

P12, L13-15 / Figure 10: - In contrast to Figure 6 you use absolute TB and Tsnow-ice values here - while for the regressions shown in Figures 3 and 4 you (at least partly) used TB anomalies? Please explain i) why you can use the absolute values here and ii) why it is possible to use equations 3 and 4 also for the absolute values. Equations 3 and 4 use absolute Tbs values. See previous comments.

We work with TB anomalies only for the first step of the regression. Then we work with the Tbs as it is written in equations 3 and 4. In figure 10 we plot the regression as a line by choosing a constant snow depth.

P13, Figure 11: Please check the caption; "at different frequencies" does not apply to the figure shown.

Yes we corrected this.

P13, L1/L6: "50V" ? Perhaps you write on P12, L17: "50 GHz at vertical polarization (50V)"? Then you have introduced this acronym.

Ok.

P13, L3/4: I am not sure I would term this behaviour "sensitivity". It is possibly better to state - like you partly did - that if the slope of the regression is < 1 then Teff originates from below the snow-ice interface while when the regression is > 1 then Teff originates from above the snow-ice interface. This makes pretty much sense given the smaller penetration depth into snow and sea ice at 89GHz compared to the lower frequencies, i.e. 10GHz or 6 GHz.

Ok the sentence has been modified.

P13, L7-9: "These linear regressions ... to retrieve the Teff ..." -> ok ... but how? Now we are at the point where I, as the reader, would like to see the "final" equation with which I can compute Teff based on (which?) TB with (which?) external or additional input data ... Here the paper kind of stops and does not go further ahead. Why? -> GC3

Ok we have added the final equations to retrieve Teff.

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 3.97) + b_{2(freq,pol)}, \quad (5)$$

for the regression using 10V TB

$$T_{eff(freq,pol)} = b_{1(freq,pol)} \cdot (T_{Snow-Ice} - 4.01) + b_{2(freq,pol)}, \quad (6)$$

for the regression using 6V TB

P14, Table 3: Please state in the caption what the source for Tsnow-ice and Teff are.

Ok it has been added. "Using Teff and Tsnow-ice provided by the simulated dataset using MEMLS and the thermodynamical model."

P14, L2-8 / Figure 12 - Why do you use SIC from a weather forecast model? This is not understandable given the multitude of products available in Bremen. - You use Eq. 3 and hence first need to compute the TB anomalies ...? - Am I right in assuming that the snow-depth input into Eq. 3 is the one computed with Eq. 1 and shown in the first row of Figure 12? - You use and show a multiyear ice concentration product ... why? Is this to demonstrate / illustrate that your approach is able to compute snow depth over multiyear ice as well? While it is certainly a valuable product one gets the impression that the multiyear ice area increases during winter. Even ice drift seems not capable to explain the substantial spread of multiyear ice into the Eastern Arctic Ocean. - What is the cut-off MYI concentration value used in Figure 12, last row? In other words: What is the minimum MYI concentration displayed? It seems not to be 1%. - Please provide a measure of the actual ice cover - for instance by providing the 15% sea-ice concentration isoline in all 9 images of Figure 12. - In almost all images in Figure 12 there are tiny, noisy white dots. Where to these come from? Can you remove them?

We use the SIC to filter the AMSR2 data and to consider only the areas with 100% SIC. The white dots you see are just blank because we use AMSR2 L1R swath data. The minimum MYI concentration displayed is 0% meaning that there is first year ice or no ice at all.

P14, L9-13 / Figure 12 - This paragraph needs to be rewritten. I have difficulties to follow the justifications about the larger snow depth and snow depth evolution north of Greenland and the Canadian Arctic Archipelago. Yes, we know Warren et al. (1999) but there are more recent papers to check that out. Since you have been using OIB snow depth data it would be fairly easy to look into respective papers (Webster et al.) in which these data were analysed and discussed. There has also been a recent update of the Warren et al. (1999) climatology by Shalina and Sandven. Even though its data are from the past as well it is certainly worth to take a look. In addition, since the paper lacks so far the justification why - now with the new regression - also snow depth retrieval over multiyear ice is potentially possible, it would be important to get back to this issue here and to also mention the work done by other members of the group in Bremen (Rostosky et al., Frost et al.). Nothing is specifically stated about the snow depth (quality) in the rest of the Arctic. It is in particularly not understandable why large parts of the first-year ice cover have been omitted.

We added the references. The discussion about the ice type has been added (see the previous comments) The paragraph has been rewritten:

"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)."

First year ice areas are not omitted, we only filter out the areas which are not 100% ice. The MYI concentration product shows the MYI concentration from 0% to 100% which mean that there are also areas with no ice at all.

P14, L14-19: - "âĹij-30degC" -> How do you know? Arctic wide? Which data source? - I would rethink about the November temperature you mentioned so explicitely. If it is -5 degC then the snow-ice interface temperature is colder than the atmosphere everywhere. - While it is correct that for Jan. and Apr. there are areas where a thick snow cover nicely aligns with warmer Tsnow-ice values there are also regions where a thick snow cover nicely aligns with particularly cold Tsnow-ice. This should be discussed further. - "Note that we can observe ..." -> If this is the case then this would be very confusing and I would strongly recommend to either remove or flag these areas using an appropriate sea-ice concentration threshold - appropriate in the sense that application of the flag allows a Tsnow-ice bias due to the open water of X Kelvin ... X = 2K? ..... Alternatively, you could - as has been done for the original snow depth retrieval (these people were smart) - correct the input TBs for the fraction of open water. Perhaps, by superposing 15% sea-ice concentration isolines on each image of Figure 12 helps to find out where these sea ice margins are located.

It is ERA-interim air temperature at 2m. We added precision about the air temperature observed. We added a reference : Perovich, D. K. and Elder, B. C.: Temporal evolution of Arctic sea-ice temperature, Annals of Glaciology, 33, 207-211, 2001.

Page 15, L1 until P16, L6: - in L2: "highest values" -> of what? - in L6: "Under the same conditions, a higher ice thickness will lead to a lower Tsnow-ice value"-> really? Lets consider a 4 m thick, a 2 m thick and a 1 m thick ice flow, all at -30degC air temperature and all with 10 cm snow on top. Isn't the heat conduction through the snow the main driving factor for the ice-snow interface temperature? - In L1 next page: "positive correlation" ... I suggest to be more careful with this statement unless you can provide evidence that you indeed observe such a correlation by, e.g., picking specific subregions, compute correlations on a daily basis and present time series of these. GC4

"highest MYI concentrations"

I give no comments to the conclusions yet as they might be rewritten after the revision. Typos: P2, L1: "reduced" -> "reduces"

P2, L25: "of the" -> "at the"

P2, L26: "in the medium" -> perhaps better: "into the medium"?

P3 L1: "Secion" -> "Section"

P3, L9: "dataset" -> "datasets"

P14, L14 & 16: Add "C" behind the degree sign of the temperature.

P16, L5: "developped" -> "developed"

Typos corrected.