Response to reviewer 1

Reviewer comment:

Overall, I found this study well written, straight to the point and very interesting. The EFAST decomposition is a simple yet robust method to explore whether an individual parameter contribute more or less than its coupling with other parameter in a qualitative AND quantitative way. The paper does a really good job describing the coupling and non-coupling effect of the different snow parameters on the TBs and the different GRs. Given the fact that this paper relies on MOSAiC snow data to estimate the range of variability of the snow and ice parameters, I think it would be valuable to have results of this parametrization that fits the MOSAiC TBs to confirm that the proposed configuration still falls within the observations range.I think this study is well suited for publication in The Cryosphere as it fits very well its scope, but some minor adjustments are needed prior publication.

Thank you for your valuable comments. We accept the reviewer's constructive comments. We will add additional experiments and enhance the clarity of the methodology section in the revised manuscript. Please see our response (blue text) below

Specific comments

Given the fact that this paper relies on MOSAiC snow data to estimate the range of variability of the snow and ice parameters, I think it would be valuable to have results of this parametrization that fits the MOSAiC TBs to confirm that the proposed configuration still falls within the observations range.

We have added an additional TB simulation experiment using MOSAiC measurements together with collocated AMSR2 TBs. In this experiment, we mainly used the single-layer snow configuration corresponding to Sect. 4.1.1 of the sensitivity analysis. Because direct measurements of snow liquid water content during MOSAiC were not publicly available, we therefore restricted this comparison to the winter period, when dry snow conditions are expected to dominate. Values for the snow depth, density, temperature and radius were taken from the MOSAiC measurements. For each snow observation site, profile measurements were averaged to obtain a representative value for the corresponding snow column.

To make the modelled TBs more comparable with AMSR2 observations, we also included sea ice and atmospheric datasets in the forward simulation. Specifically, the SMRT model was first used to simulate the microwave emission from the snow-covered sea ice surface. The simulated surface TBs were then propagated through the atmosphere using the Wentz atmospheric radiative transfer model (Wentz and Meissner 2000).

Tab. R1 Snow, sea ice and atmosphere configurations used in the forward simulation

Layer	Parameter	Setting or Source
Snow	Depth	MOSAiC measurements
	Density	
	Temperature	
	Radius	
	Stickiness	0.15
Sea ice	Thickness	Same as that in the original Manuscript Tab. 4
	Density	
	Temperature	
	Radius	
	Brine volume fraction	
	Porosity	
	Multi-year ice concentration	Dataset from University of Bremen (Ye and Heygster, 2015)
Atmosphere	Total water vapour	ERA5 reanalysis (Hersbach et al, 2018)
	Total cloud liquid water	

Overall, this SMRT configuration can reproduce the general magnitude and temporal variability of the AMSR2 observed TB, particularly at the intermediate-frequency channels from 18 to 36 GHz (See Fig. R1). At the low-frequency channels (6 and 10 GHz), the simulated TBs are systematically lower than the AMSR2 observations. This discrepancy is likely related to the stronger sensitivity to sea ice temperature and brine volume fraction. The best agreement is found at 18, 23 and 36 GHz. At 89 GHz, both the observed and simulated TBs exhibit much stronger short-term variability. The model captures part of the observed TB fluctuation and the increase in late winter. Overall, the comparison supports the use of the adopted snow and sea ice configurations as a physically plausible basis for the sensitivity analysis.

Following your suggestion, we have included this analysis in the Supplementary Material.

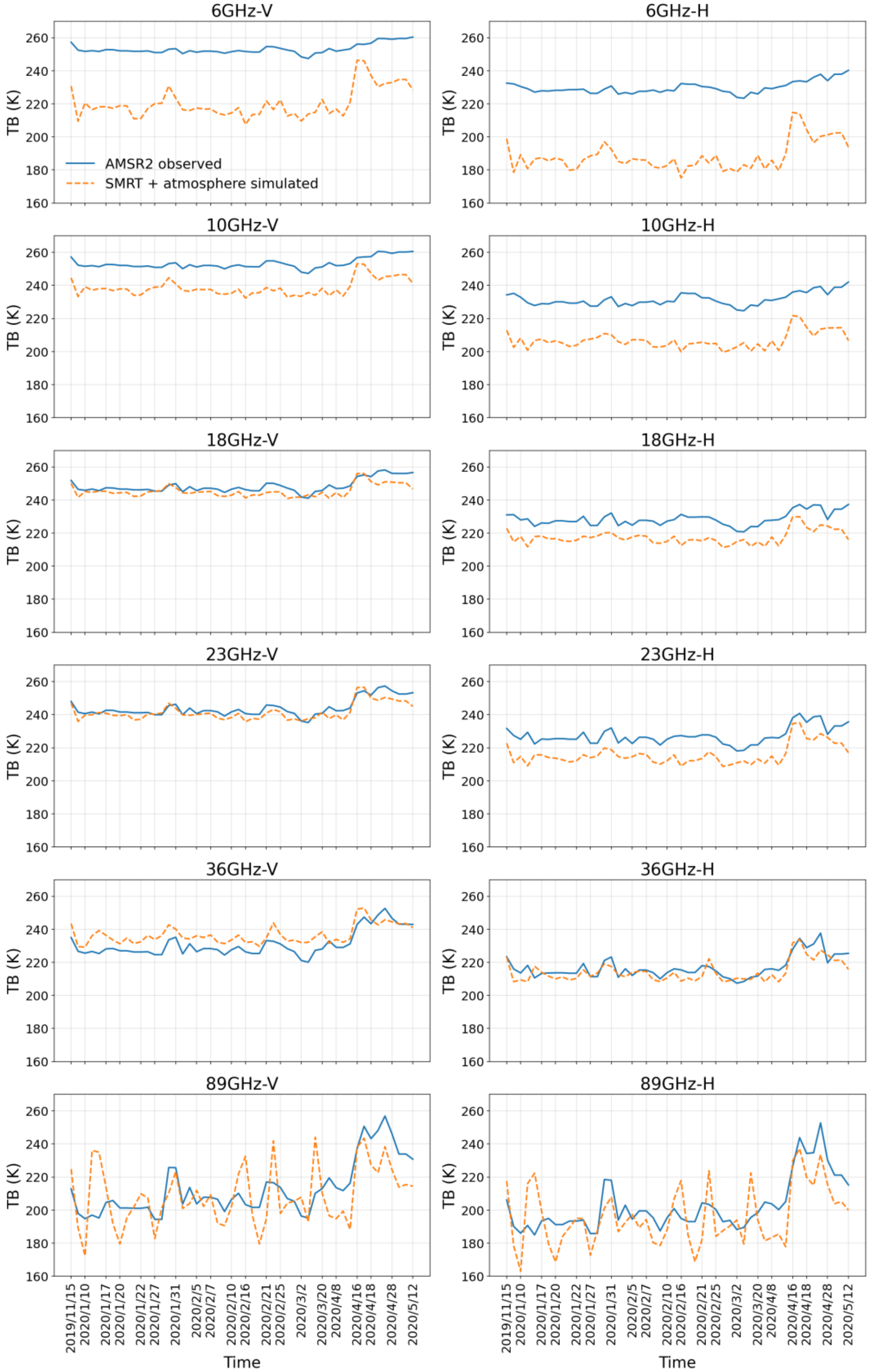

Fig. R1 Time-series comparison of SMRT-simulated TBs and AMSR2-observed TBs during the MOSAiC winter period.

Moreover, following the suggestions of the other reviewers, we conducted a sensitivity analysis using the exponential microstructure model instead of the sticky hard sphere (SHS) microstructure model. The results are broadly consistent with the main conclusions of this study, and detailed experimental results are provided in the Supplementary Material.

Although the authors mention in the text that the "global" term refers to the full parameter space, having it in the title can be quite confusing as it mostly focuses on Arctic snow. In general, the paper does a very good job describing the theoretical coupling between the ASMR2-3 frequencies, but given the title there is this feeling it would be more connected to observations. The Section 3.2 "Microwave radiometer configuration" is in data yet just describes the AMSR2 frequencies. If no observational TBs are used, this should be moved to the Method section.

The Global Sensitivity Analysis (GSA) is a specific terminology, therefore, we would prefer to retain the term "global sensitivity analysis" in the title.

As for the Section "Microwave radiometer configuration", although the comparison of satellite measurements and model-based simulations is not presented in the main manuscript. Following the reviewer's suggestion (see previous comment), we have added model–observation comparison experiment in the Supplementary Material. We therefore would like to keep this section in the Data section and add more detailed information regarding the configuration of AMSR2 (Also see reply to the next comment).

Still in the section 3.2 or later in the text, I am surprised nothing is said about the major footprint's size difference between the 6GHz and the higher frequency channels (36 and 89 GHz. For snow depth retrieval from satellite measurement, this cannot be ignored as the 6GHz footprint is tens of km wider than the 36GHz, so the GR36/6 may also show something artificial due to the heterogeneity between the two footprints.

In the revised manuscript, we plan to add a description of the AMSR2 spatial resolutions in Section 3.2, Page 7:

"AMSR2 measures upwelling microwave TBs at six frequency bands centred at 6.9,

10.7, 18.7, 23.8, 36, and 89 GHz (henceforth denoted as 6, 10, 18, 23, 36 and 89 GHz for simplicity), operating at a conical incidence angle of approximately 55°. The corresponding footprint sizes are approximately 62 × 35, 42 × 24, 22 × 14, 26 × 15, 12 × 7, and 5 × 3 km, respectively, from the lowest to the highest frequency."

The present SMRT-based retrievability analysis assumes a horizontally homogeneous snow and ice scenario and the same footprint across channels. We have added the description in Conclusion Section (Page 29):

"It should also be noted that the present SMRT-based retrievability analysis assumes a homogeneous surface and the same footprint across channels. In practical applications, footprint mismatch between low- and high-frequency channels, e.g. GR(36/6), could potentially introduce additional artefacts to snow depth retrieval. The resolution-harmonized Level-1R (L1R) TB data from JAXA may be useful here (Maeda et al. 2016)."

L255-260 and Tables 2-3: how is snow ice and superimposed ice modelled in SMRT? Are you using fresh ice layer? Snow with such high density (>500) can be tricky to configure in SMRT as some permittivity models can't characterize snow with density that high. I would maybe suggest to better describe the permittivity model used for each layer (snow, ice, fresh, dry, wet etc..)

We are aware that existing snow microstructural assumptions and scattering formulation (Sticky hard spheres + Improved born approximation) may become unstable in the intermediate- to high-density regime. In addition, in response to comments from the other reviewers, we revised the description of the "snow ice" layer in the manuscript. Because "**snow ice**" layer is very rare in the Arctic and the term may therefore cause ambiguity, we have replaced it with "**saline interlayer**" layer. Apart from this change in terminology and the corresponding revisions throughout the manuscript, the parameter settings used in the experiments remain unchanged.

We therefore took three precautions in our study:

1) In the SMRT simulations, the saline interlayer is treated as a thin sea ice layer rather than a snow layer. The difference is in the physical parameterisation of the layer: when treated as sea ice, the dense saline layer is represented as an ice-rich medium with brine inclusions, rather than as a high-density snow layer composed of ice grains embedded in an air matrix.

2) We limited the maximum density of snow layers (wind slab and depth hoar) to 500 kg m⁻³. Although the MOSAiC observations indicate that locally higher snow densities may occur, a density of 500 kg m⁻³ already corresponds to an ice volume fraction of approximately 0.55, which is slightly above the upper practical limit for applying the IBA+SHS simulation (0.5 given in Picard et al. 2022). We checked the simulated TB over the density range used for the snow layers. The 3D TB figures (Fig.6 – 9 in manuscript) show smooth and continuous variations over 200–500 kg m⁻³, without abrupt fluctuations or discontinuities. This gives us confidence that the IBA+SHS configuration behaves stably within the snow density range.
3) We used the dense snow correction available in SMRT. When the ice volume fraction exceeds 0.5, this option treats the medium as air inclusions embedded in an ice matrix rather than ice particles embedded in an air matrix.

To describe this more clearly, we have added a model setup table to the Supplemental Material (Tab. R2).

Tab. R2 SMRT model setups

Topic	Snow	First year ice (including saline interlayer and superimposed ice)	Multi-year ice
Scattering theory		Improved born approximation (with dense snow correction)	
Microstructure Representation		Sticky hard spheres	
Surface/interface scattering models and substrate		Default flat/Fresnel interfaces were used; a water substrate was added below the sea ice.	
Permittivity model	ice_permittivity_matzler87	ice_permittivity_matzler06 brine_permittivity_stogryn85	ice_permittivity_matzler06 polder_van_staten
Radiative		Discrete Ordinate Radiative Transfer solver	

transfer solver	
SMRT version	1.5.1

How saline was the snow? A 5% of brine volume fraction isn't something we can easily represent, as BVF is not something we directly measure on the field. It could be better to explicitly say the salinity value set in SMRT to get this BVF of 5%, as Figure 2 also shows the salinity of the snow in PSU.

In this study, we didn't treat the ordinary snow layers as saline. The salinity of the snow layers, including wind slab and depth hoar, is set to 0 PSU in the SMRT simulations. The reason is that the MOSAiC measurements show that most of the snowpack has very low or negligible salinity, while enhanced salinity is mainly observed near the snow–ice interface. This near-interface layer is also characterised by higher density and is physically different from the overlying snow. Therefore, in our model configuration, this saline and dense transitional layer is represented as a "saline interlayer" layer ("snow ice" layer in the previous version).

The BVF=5% in Table 4 is used for basal first year ice. It is based on MOSAiC measurements, we found that BVF generally fluctuates around 5% (Fig. R2). Although BVF increases to about 10% at deeper depths, around 1.5–2 m, these deeper layers are expected to have limited influence on the passive microwave signal because the penetration depth is less than 1 m at 6 GHz. Therefore, we used BVF = 5% for first year ice.

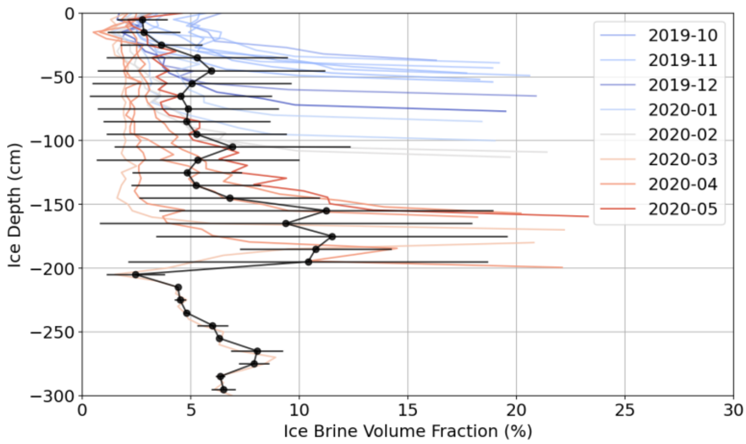

Fig. R2 Brine volume fraction measurements (First year ice) during MOSAiC

Figure 3, 4 and 5: the author's choice of underlying the TSI value is quite confusing and sometime makes the results not readable. It would be better to just write the

numbers (such as for Figure 3-b 18H where the author forgot to put the underline)
We have revised Figs. 3, 4, and 5.

Figure 4 is mostly empty, I wonder if there would be a better way to present these sparse results.
Reply: Thank you for this suggestion. Fig. 4 is sparse because many parameters have very low sensitivity at several AMSR2 channels. We considered alternative ways to present the results, including compressing or narrowing columns with generally low sensitivity, such as some temperature columns. However, we found that changing the column width would alter the visual meaning of the matrix and could unintentionally imply that these parameters are less important a priori than the others, rather than simply having low sensitivity under the tested conditions and channels.

Therefore, we decided to retain the full matrix structure with equal column widths. The empty cells are meaningful in this figure because they indicate parameters or channels for which the sensitivity is below the display threshold, and their contrast with the filled cells highlights the channel- and layer-dependent distribution of sensitivity.

For the figures showing the GR as function of snow depth and snow density (Figures 6, 7, 8 and 9), I would suggest removing the X-Y projection as it takes a lot of space and decrease the readability of the results and in a lot of case, they are showing no variability at all. They could be added as Supplementary material, according to the author’s decision.
We have moved the X–Y projection panels from Figs. 8 and 9 to the Supplementary Material. We retain the X–Y projections in Figs. 6 and 7 because, for readers who are less familiar with the concept of retrievable range, the projections help illustrate how the averaging kernel diagnostics are converted into the retrievable domain.

L446: “The 89 GHz TBs are also susceptible to atmospheric effects…” This is also true for the 36GHz and in a lower extent the 18GHz.
We have revised the sentence. The new text reads (in Section 4.2.1):
“Atmospheric effects can affect the measured TBs at several AMSR2 channels. This effect is strongest at 89 GHz because of its higher sensitivity to water vapour and cloud liquid water, but it is also non-negligible at 36 GHz and, to a lesser extent, at

18 GHz. The water vapor influence is similar there, just slightly lower than at 89 GHz. These atmospheric contributions can introduce additional uncertainty into snow-depth retrievals, particularly for retrievals or GRs involving the higher-frequency channels."

References

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