Response to reviewer 2

Their study evaluates the retrievability of snow depth over Arctic sea ice for the AMSR2 frequency channels. I appreciate the effort of taking a more fundamental view on the question: instead of trying out different snow depth retrievals the authors use radiative transfer modeling to test sensitivities depending on background conditions.
The introduction is well written. The methods are clearly described but could benefit from a bit of additional information (see below) and more caution regarding the use of snow ice. The Data section describes the MOSAiC data but remains a bit too vague as to how the MOSAiC data is actually used later in the model setup. The Results section is well structured, describing first the results of the different snow setups and then the retrievable ranges, see some comments for improvement below. The conclusions provide nice guidance for further developments, highlighting also the importance of snow grain sizes. The figures are well done and I congratulate the authors for visualizing the information/coupling effects of such high dimensions, without oversimplifying it.

Reply: 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

Reviewer comment:

How do the authors ensure representative sampling? From the method section I understand that the parameters are uniformly sampled, thus unrealistic input cases, that is unrealistic combinations of layer parameters or values that are rare, such as very deep snow, are possible and could influence the sensitivity. Is that right? Or is there a mechanism to ensure that the observed gradients of, e.g., temperature and density, are preserved or that the output is weighted according to the likelihood of occurrence? The use of the MOSAiC data here is not clear to me.

In our original setup, the normalised EFAST samples were mapped uniformly onto the prescribed physical ranges of each parameter.

To evaluate whether this sampling choice affects our main conclusions, we performed an additional sensitivity test using bounded Gaussian sampling. Specifically, for parameters with available MOSAiC-derived means and standard deviations, we generated EFAST samples from bounded Gaussian distributions parameterised by these statistics (see Tab. R1), while retaining the parameter range constraints specified in the original study. This allows the samples to be more concentrated around the MOSAiC-observed mean states while remaining within the physically plausible intervals.

Tab. R1 Means and standard deviations (SDs) of snow parameters derived from MOSAiC measurements and used in an additional sensitivity test with bounded Gaussian sampling.

Parameter	Depth	Density	Temperature	Radius
Unit	cm	kg/m^3	K	mm
Mean	13.2	313.0	257.2	0.37
SD	11.7	137.7	7.2	0.38

The results of this additional sensitivity test show no fundamental change in the main conclusions (Fig. R1). The most sensitive parameter in each channel remains consistent with the original uniform-sampling sensitivity test, and the frequency-dependent coupling patterns among snow depth, density and grain radius are also preserved. In particular, the dominant role of snow microstructure at higher frequencies and the strong parameter-coupling behaviour identified in the original analysis remain evident under the MOSAiC-constrained Gaussian sampling.

The EFAST framework requires a consistent sampling treatment across all input parameters in the normalised parameter space. We did not adopt Gaussian sampling as the primary EFAST sampling strategy because reliable MOSAiC-based means and standard deviations are not available for all parameters. For example, MOSAiC does not provide summer observations of liquid water content in snow, which is a key parameter in the wet snow simulations. In addition, some summer snow states observed during MOSAiC, especially very high density and large grain wet snow, exceed the validity limits of the SMRT simulation. The MOSAiC observations were used to define the physically plausible parameter ranges. Although we calculated MOSAiC-based means and standard deviations and used them in the additional robustness experiment, we did not use them in the primary EFAST sampling because of the above limitations and because the primary goal was to examine the full bounded response space of the radiative transfer model.

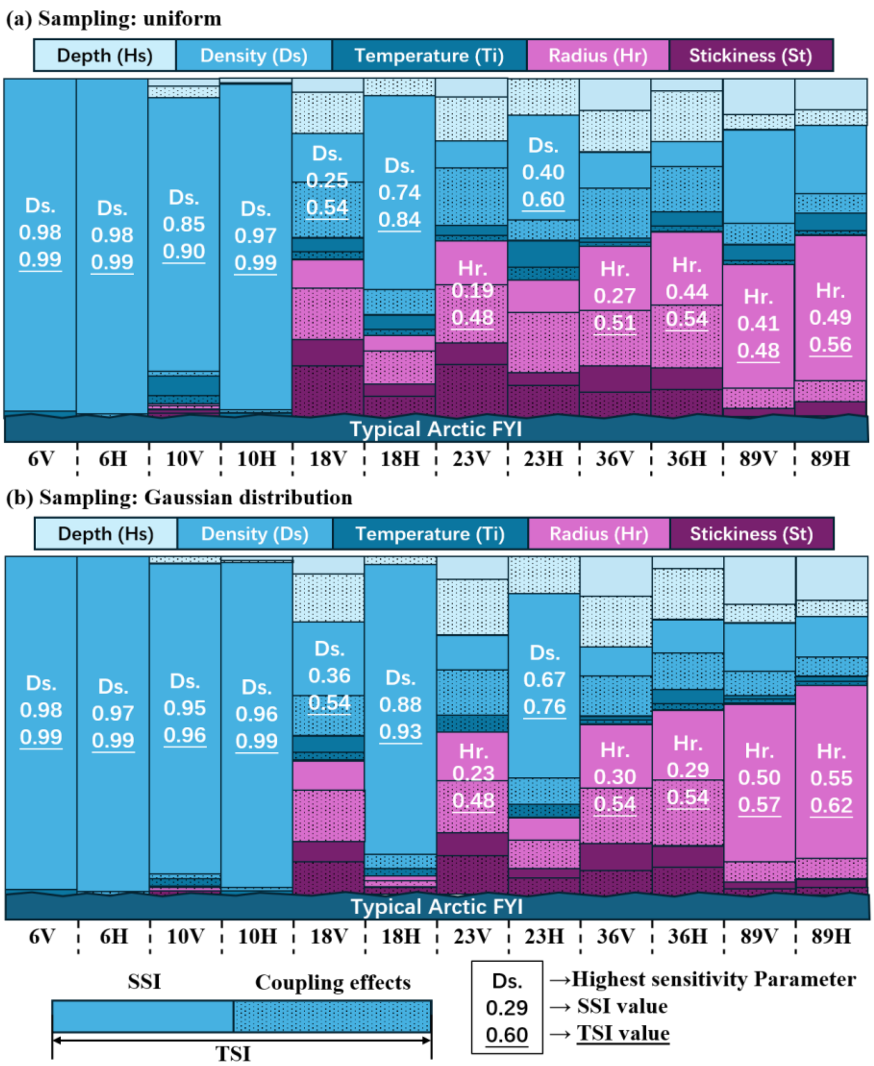

Fig. R1 EFAST sensitivity result of single-layer Arctic snow parameters under dry snow conditions. Solid segments indicate the SSI of each parameter, while dotted extensions show the coupling effects captured by the TSI. For each channel (column), the strongest single sensitivity and the total sensitivity are also given numerically.

Another general remark related to that: I think the confidence in the modeling results/snow configuration could be increased by a direct comparison, possibly in the supplemental material, of the modelled brightness temperature distributions to pan-Arctic satellite-measured brightness temperature distributions (possibly corrected for atmosphere), to see how modelled and measured TB variabilities compare (with no perfect agreement expected).

Following the reviewer's suggestion, a pan-Arctic comparison requires spatially continuous information on key snow microstructural properties, especially snow density and grain radius. These two parameters are critical for the SMRT simulations, as demonstrated by our sensitivity analysis, but they are currently difficult to obtain at the pan-Arctic scale with sufficient accuracy and consistency. Therefore, rather than performing a pan-Arctic comparison based on poorly constrained snow microphysical inputs, we conducted an additional TB simulation experiment based on the MOSAiC observations, where snow depth, density, temperature, and grain radius are directly measured.

In this additional analysis, 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 were not available in the MOSAiC dataset used here, we 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 2000).

Tab. R2 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 setting 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 Total cloud liquid water	Use ERA5 reanalysis (Hersbach et al, 2018)

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. R2). 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 background properties. 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 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.

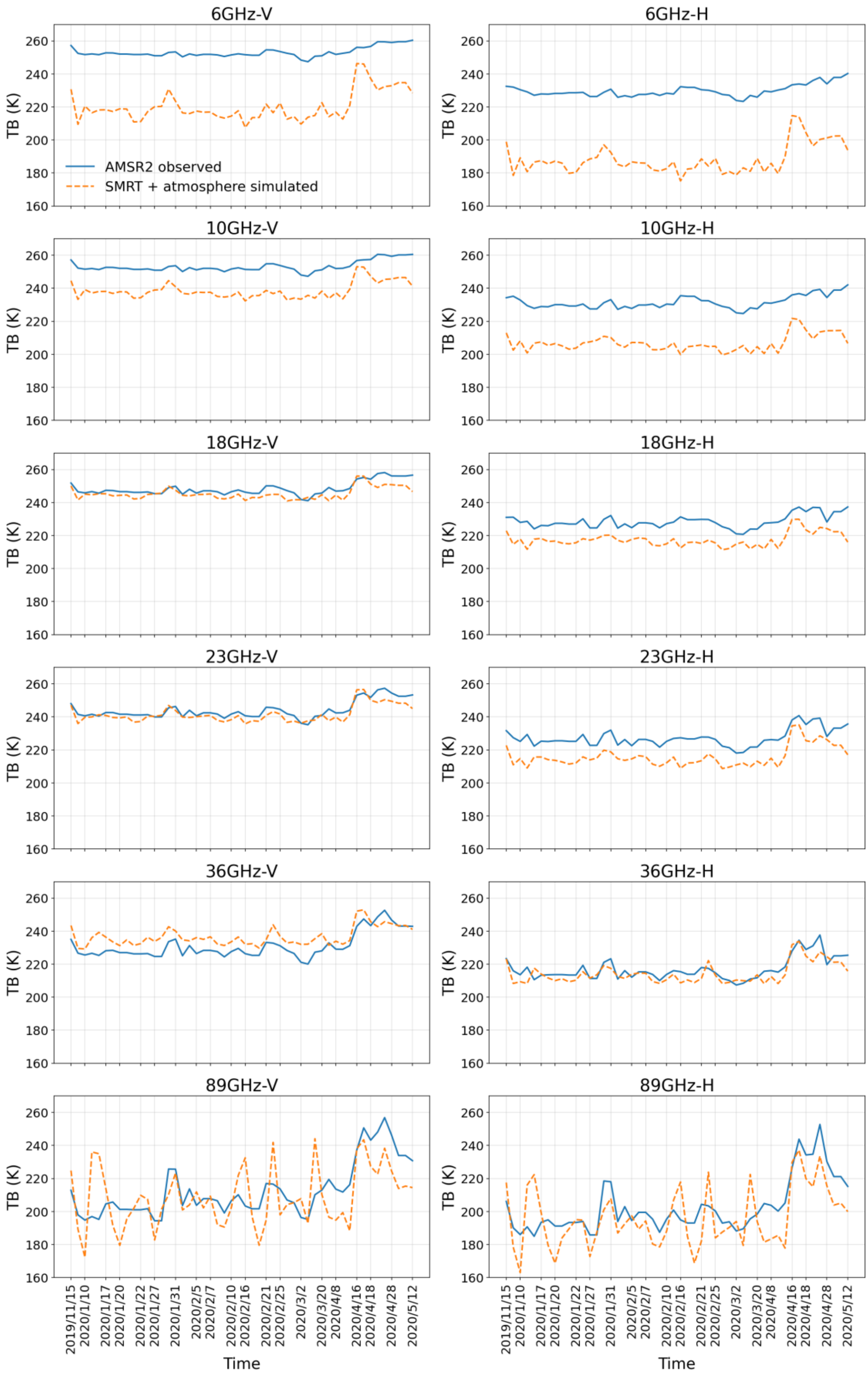

Fig. R2 Time-series comparison of SMRT-simulated TBs and AMSR2-observed TBs during the MOSAiC winter period.

Section 2.1: I recommend that the authors follow the guidelines from the official SMRT documentation: https://smrt.readthedocs.io/en/v1.5.1/publish.html providing a table with additional information about the model setup (in the supplemental material) including the surface roughness assumptions, the version number of the model and the exact way the salty snow (snow ice in Table 2) is modelled (what permittivity formulation is used)

We have added a model setup table to the supplemental material (Also see Tab.R3).

Tab. R3 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 transfer solver		Discrete Ordinate Radiative Transfer solver	
SMRT version		1.5.1	

- L. 116 : is i going from 1 to N or from 1 to n (as suggested by line 113)?

The index i denotes the input variable index rather than the sample index. Therefore, i should range from 1 to n, where n is the number of input variables. We have corrected this mistake.

- Section 2.3: While the general description of the averaging kernel as a matrix is of course correct, you could add that is 1D in your case, am I correct?

The averaging kernel matrix is one-dimensional because snow depth is the only target parameter considered.

- Section 3.1., Line 190: how are these measurements used exactly? To constrain the parameter ranges? Or to sustain realistic parameter combinations?

The MOSAiC measurements were used mainly to define variation ranges for the input parameters in the EFAST sensitivity analysis. We have added an additional sensitivity test in the Supplementary Material. In this additional test, the parameter variations were defined using the means and standard deviations derived from the MOSAiC measurements (see the reply to General Comment 1).

- Line 201/Table 4: you write about BVF for temperatures warmer than -2°C, but you only model 265 K ice. How did you come up with BVF of 5% in Table 4?

The sentence referring to Cox and Weeks (1983) (For cold ice) and Leppäranta and Manninen (1988) (for ice warmer than -2℃) describes how BVF was derived in the MOSAiC ice-core data set from measured salinity, temperature, and density. The BVF value of 5% in Table 4 was used as an idealised representative value for cold ice, rather than being calculated from the warm ice formulation from Leppäranta and Manninen (1988). To avoid ambiguity, we remove the description of "***Leppäranta and Manninen (1988) for ice warmer than -2 ℃***" from the original sentence.

- Section 3.2.: I suggest to add AMSR2 footprint sizes

Agreed and added

- Section 3.3.: snow ice formation: I suggest a bit more caution with using this term in the context of Arctic sea ice. To my knowledge flooding is common in the Antarctic (the Maksym and Jeffries paper quoted in line 217 and line 239 is also about Antarctica, which should be clarified), but the occurrence in the Arctic is still not clear. Also, the Merkouriadi study quoted later in line 360 talks about potential and not observations at large scale, please formulate accordingly. It is not clear to me whether the use of snow ice is backed by the MOSAiC observations. That is not to say that there is no salty snow (commonly observed e.g. on fast ice) but to be careful with the flooding hypothesis. Finally, the density values listed in Table 2 go up very high, and scattering formulations tend to break down at intermediate/high densities, see Picard, G., Löwe, H., and Mätzler, C.: Brief communication: A continuous formulation of microwave scattering from fresh snow to bubbly ice from first principles, The Cryosphere, 16, 3861–3866, https://doi.org/10.5194/tc-16-3861-2022, 2022. Please have a look whether any issues are observed with regard to that.

In the revised manuscript, we have replaced the term "**snow ice**" with "**saline interlayer**" throughout the manuscript, figures, tables, and Supplementary Material. We have revised the description of saline interlayer in Sect. 3.3 (Page 8) and now use more cautious wording.

"***We include an idealised saline intermediate layer near the snow–ice interface. This layer represents a possible dense and saline transition between the snowpack and the underlying sea ice. For simplicity, we refer to this idealised intermediate layer as saline interlayer in the present study. The formation of saline interlayer may involve several processes. In Arctic sea ice, enhanced basal snow salinity may also arise from upward brine migration from the ice surface into the basal snow (Domine et al. 2004; Nandan et al. 2017; Mallett et al. 2024). Therefore, we treat this layer as an idealised sensitivity scenario to examine the potential radiometric impact of a dense saline layer at the snow-ice interface. Given the limitations of the SHS model in simulating high-density snow (Picard et al. 2022), the saline interlayer is treated as a thin sea ice layer rather than a snow layer in the SMRT simulation. In this parameterisation, the saline interlayer 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.***"

During the design of our SMRT simulation, we were aware of the issue discussed by Picard et al. 2022, that existing snow microstructural assumptions and scattering simulation (Sticky hard spheres + Improved born approximation) may become unstable in the intermediate- to high-density regime. We took three precautions:

1) In the SMRT simulations, the saline interlayer is treated as a thin sea ice layer rather than a snow layer (See Tab. R3). 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 (See Tab.R3). 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. . This medium inversion approach is also mentioned by Picard et al. (2022) as a possible treatment for dense snow.

-Section 3.4/ Table 4: what is the source of e.g. the radius values and the BVF values? Is it based on literature or MOSAiC data?

The radius values were derived from MOSAiC. The BVF value is also based on MOSAiC ice-core data. BVF generally fluctuates around 5% (Fig. R4). 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 at 6 GHz is below 1 m. Therefore, we used BVF = 5%.

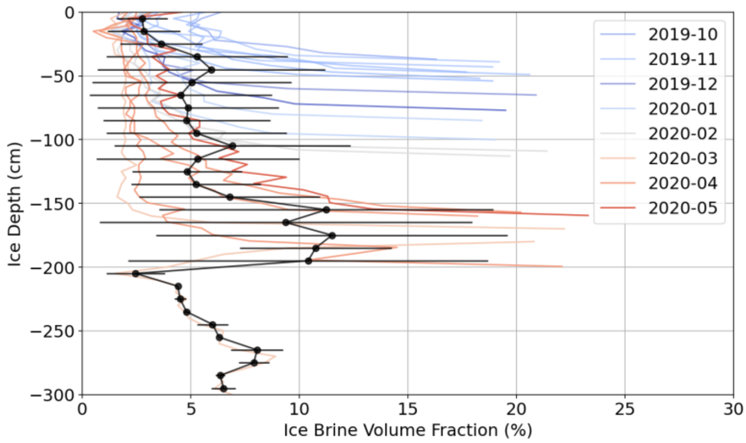

Fig. R4 Brine volume fraction measurements (First year ice) during MOSAiC

- Figure 1: You could consider adding a panel giving the number of observations per snow depth/horizontal bars.

We have revised Fig.1 (See Fig. R5).

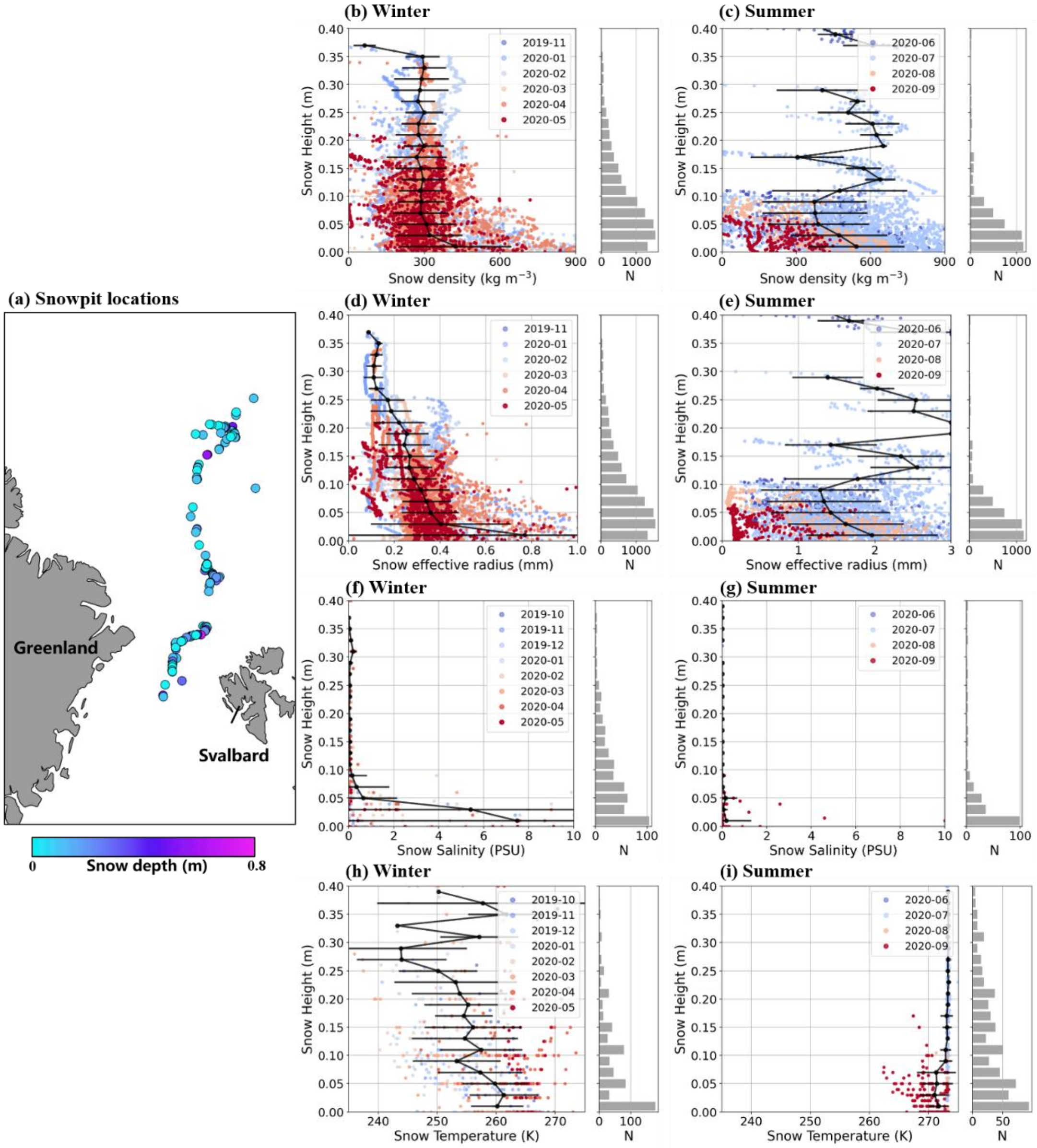

Fig. R5 Revised Fig. 1 in the manuscript.

- Section 4, Line 307: why is the temperature not shown for wet snow? I would think it is the biggest contributor with wet snow being more similar to a black body?

In our wet snow sensitivity analysis, snow temperature was not included as a varying parameter because it was fixed at 273.15 K. This choice was based on the MOSAiC observations, which show that wet snow temperature varies only weakly during the melt season, with a mean value of 272.4 K and a standard deviation of 1.9 K (See Fig.

R5). However, the snow temperature is not allowed to be lower than 273.15 K when snow liquid water is simulated in the SMRT model. Therefore, we set the wet snow temperature to a fixed value of 273.15 K and did not include it in the sensitivity analysis.

- Line 383: "finite depth" please be more specific, I assume snow is always of finite depth

We thank the reviewer for pointing this out. What we intended to express is that, when the wet snow layer is not thick enough to completely attenuate the contribution from the underlying interface, reflections from the superimposed ice layer can still affect the simulated TBs. We have revised the sentence accordingly in Section 4.1.3, Page 17.

"***When the wet snow layer is thin, e.g. <1 cm, it may not fully attenuate radiation from the lower boundary, so, the reflections from the underlying superimposed ice and residual microstructural scattering can still contribute to the observed signal.***"

- Section 4.2: I could not follow on which simulation setup this section is based. Are these extra simulations? Is the single-layer snow used? But then, how can we get snow depths up to 1 m when the range was limited to 60 cm in the previous section? Is wet snow excluded? Please clarify.

Sect. 4.2 is based on additional simulations, rather than on the EFAST sample sets used in Sect. 4.1. Specifically, the analyses in Sects. 4.2.1 and 4.2.2 use an idealised dry single layer snowpack over typical Arctic FYI. Snow temperature and stickiness are fixed at 260 K and 0.1, respectively, and only snow depth, density, and grain radius are varied. The snow depth range in Sect. 4.2 was intentionally extended to 0–1.0 m to diagnose the saturation behaviour of single-channel TBs and GRs and to define the retrievable envelope. Wet snow is excluded from Sect. 4.2. This choice was made because most existing passive microwave snow depth retrieval algorithms over sea ice have been developed and applied primarily for dry snow conditions. We have clarified this simulation setup in the revised manuscript, Section 4.2, Page 19:

"This Section is based on additional simulations, rather than on the EFAST sample sets used for the global sensitivity analysis in Sect. 4.1. Specifically, the analyses in Sects. 4.2.1 and 4.2.2 use an idealised dry single layer snowpack over typical Arctic FYI. Snow temperature and stickiness are fixed at 260 K and 0.1, respectively, and only snow depth, density, and grain radius are varied. The snow depth range is intentionally extended to 0–1.0 m in Sect. 4.2 in order to diagnose the saturation

behaviour of single-channel TBs and GRs and to define the retrievable range."

- Figure 6: I am surprised to see no sharper gradient between 0 cm snow and the rest, is 0 snow actually modelled or is there always a thin snow layer present?

Yes, we used a very thin snow layer (0.001m). This very thin layer was introduced to avoid an abrupt numerical transition between a snow-covered surface and a bare ice surface. It is negligible compared with the 0 – 1 m snow depth range in Sect. 4.2 and does not affect the diagnosed retrievable ranges.

- Line 35: "most weather and all-sky conditions": redundant

Deleted

References

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