Response to Reviewer2

Comments from review

Response

General Comments

This is an interesting paper that combines the new Community Firn Model (CFM) with active (Snow Radar) and passive (UWBRAD and SMOS) microwave observations and an emission model to characterize firn stratigraphy at high-elevation sites in Greenland and Antarctica. The CFM is used to simulate density measurements. The SnowRadar is used to detect and then characterize high-density layers within the firn. Density profiles and high-density layers are used as inputs into the emission model. Model results are then compared to the microwave observations.

The topic and scope of the manuscript is relevant to the Cryosphere. However, as pointed out by Reviewer #1, the paper (1) lacks a coherent structure to guide the reader though the analysis, and (2) lacks a discussion about the results and the overall broader relevance of the study to the field. I would strongly suggest a major revision to improve the readability of the manuscript.

Specific Comments:

Reviewer #1 did an ~excellent job~ at pointing out most of the major issues in this paper in Specific Comments (1, 3-15). I don't have too much more to add to this.

I would only disagree with Reviewer 1 on Specific Comments (2) – on detailed comparisons with Houtz et al. (2019, 2021) and Mousavi et al. (2021). Although there may be some similarities in the emission models, the focus of those studies is detecting meltwater in the lower-elevation percolation and ablation zone. This study focuses on high-elevation sites in what is typically the dry snow zone, which in some year's experiences extreme melt events. I don't think the comparison would be particularly relevant or useful.

1 -The introduction is too long, particularly compared with the length of the other sections and the overall manuscript.

I think much of the information in the introduction could more effectively be distributed into the main text. Specifically, following line 66 (In this paper…). For example, the details of the UWBRAD instrument, the CFM, and the Snow Radar. Following these descriptions, there is a relatively detailed description of the model.

A critical concept that is somewhat missed in the introduction, and a significant strength of the method, is the concept of refreezing high-density layers. Over the last decade, extreme melt events in the interior of Greenland have become more frequent, with melting detected at Summit in 2012, 2019, 2021(including rain!). These melting trends will likely continue, which will *routinely bury high-density layers in the firn, and ultimately alter the interior structure of the ice sheet, which has mass balance implications.*

From the perspective of EM modeling, typical dry snow models with layered firn will need to be adapted to account for these high-density layers, which can range from simple ice layers (this paper), to layers formed via shallow or deep vertical percolation of meltwater, with larger, vertically distributed ice structures (e.g.,

10. *C. Jezek et al., "500–2000-MHz Brightness Temperature Spectra of the Northwestern Greenland Ice Sheet," in IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 3, pp. 1485-1496, March 2018, doi: 10.1109/TGRS.2017.2764381.)*

Line 56 states: The strongest echoes in a radar echogram, for example, show the position of abrupt permittivity changes that usually correspond to the position of refrozen melt layers (Jezek and others, 1994; Zabel and others, 1995). An alternate or additional reference with high-density layers that are closer in structure to what you might find in cross-over sites is

*Culberg, R., Schroeder, D.M. & Chu, W. Extreme melt season ice layers reduce firn permeability across Greenland. Nat Commun **12**, 2336 (2021).* https://doi.org/10.1038/s41467-021-22656-5.

Thank you for the comments. As in the response to the first reviewer, we will shorten the introduction part of the paper and put the detailed information into the "Method" section.

Thank you for the suggestion on the refrozen layers. This is a really important part of our work. The previous microwave radiometry models have not included the effects of these refrozen layers for the high elevation area in Greenland. We will include the information provided by the reviewer and emphasize the inclusion of refrozen layers.

2 -The manuscript structure is difficult to follow.

I agree with Reviewer #1's suggestion for a more formal structure: Introduction → Methods → Results → Discussion → Conclusions. Some suggestions: I might start with a flowchart linking models with the data sets. I might next introduce the model – which nicely provides the emission concept (Fig. 8) and instantly clarifies to the reader the objective. I might then follow with the details of the input data. Then the model results. Then comparisons with UWBRAD data for Greenland only (#3 below). Then a strong discussion which is currently missing from the manuscript.

Thank you for the comments on the flow of the paper. We will revise the paper according to the suggested formal structure as Introduction → Methods → Results → Discussion → Conclusions. As responded to the first reviewer and in comments 1, we will shorten the introduction and put the details in the "method" section.

3 -The paper would be much stronger if it focused on just Greenland.

The Antarctica comparison seems out of place in the manuscript. The paper starts out with a model that includes high-density layers, and data from the CFM, the SNOW RADAR, and UWBRAD over Greenland. The paper then shifts gear to Dome C, a site where high-density layers do not form, and a model comparison with a different instrument (SMOS). Perhaps the general idea was to compare sites with different firn characteristics. If that were the case, it would be more straightforward from the perspective of the reader to include a UWBRAD comparison between sites (UWBRAD data was collected at Dome C) or a SMOS comparison between sites. But, I don't think that this comparison is needed for this manuscript, Greenland, with a strong discussion section, is sufficient.

Thank you for the comments. We will put this result to the discussion section as a broader relevance to the field

The horizontal correlation provides a tool to interpret the V and H angular dependence brightness temperature. It can also help to interpret the SMAP V and H brightness temperature data over the region with perennial aquifer.

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4 - The manuscript lacks a discussion section that describes the study relevance.

Thank you for pointing that out again. We will add a discussion section to the manuscript. The major points will be discussed in the study relevance is listed below:

1. The density fluctuations show strong effects in Brightness temperature.
    a. Strong reduction on the UWBRAD TB
    b. Angular and polarization dependence in SMOS TB.
2. This work shows that passive microwave can be used as a tool to infer the density fluctuations remotely. There is no way to measure the density fluctuations except for in-situ measurement previously.
3. Understanding the density fluctuations is important in characterizing the mass balance of polar firn.
4. The radiative transfer model in this work can help interpret the TB data over Aquifer region.
5. Help reduce uncertainty in the ice sheet temperature profile retrieval.

Technical Corrections

Line 14 - locations in the Greenland Ice Sheet - > locations on the Greenland Ice Sheet

Line 14 - and at the Dome C location - > and at Dome C

Line 15 - Borehole in situ measurements - > Borehole measurements

Line 65 - Kirchhoff's Law[Tsang 2001] - > add space

Line 131 - T41(71.08N,37.92W) - > add space

Line 140 - Summit station, Greenland - > Summit Station, Greenland

Line 147 - from Neutron Probe of Morris and Wingham, 2011 - >

from the Neutron Probe Morris and Wingham, (2011)

Line 153 - 9.4cm - > space

Line 160 - In-situ Measurements - > in situ measurements

Line 180 - X-Ray - > X-ray, also throughout text

Line 184 – Table 3: Latitude and Longitude for crossover points of 2017 UWBRAD and Snow Radar Measurements - > Table 3: Latitude and longitude for crossover points of 2017 UWBRAD and Snow Radar measurements

Figure 4, 5, 6 – Sizes of plots are different (Fig. 4) – please correct. Reverse x- and y- axes, so density is vertical, which is the typical orientation.

Line 276 - Tan et al 2020 – Tan et al., (2020)

Line 279 - Figure 9: - > remove colon

Line 282 - Figure 10: - > remove colon

Lines 290 - ð• Ÿ • . ð• Ÿ ” ð• Ÿ ‘ (0.35g/cm^3 in density) - > add space

There are many places with issues with spaces (or lack of spaces), punctuation (especially random colons), notation, un-needed capitalization (particularly in table and figure captions). Please give the manuscript a ~very careful review~ for these issues during the revision.

Thank you for the careful review of our paper. We will attend to all these issues in the revision.