Authors Response to Reviewers

Montpetit et al.

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1 Response to Reviewer #2

1.1 General Comments

The authors present a study applying a Bayesian retrieval algorithm to estimate snow water equivalent, applied using the SMRT radiative transfer model, and priors derived from the SVS-2 land surface model, with airborne radar observations from the University of Massachusetts radar instrument, and intensive field data from snowpits. The algorithm achieves retrievals with RMSE less than 30 mm across several different experiments; as 30 mm threshold required for the proposed Terrestrial Snow Mass Mission (TSMM), these results are highly significant. The results do some really intriguing work exploring the sensitivity of the retrievals to prior estimates and their uncertainty, which will be of great value to the community. The results present a very interesting contribution to the literature of using these type of retrievals, and should be published directly. Adding one more aspect of the analysis in discussion is, in my opinion, critical to really understanding these results, however.

Retrieving SWE from radar measurements is an under constrained problem. To solve this, Bayesian methods optimally weigh priors estimates of snow properties and the radar observations. Prior configuration is a condition for obtaining meaningful results, and it's not clear whether the prior is accurately configured here. Specifically, the prior uncertainty (implicitly) specified for SWE appears to be set to be set too low. Thus, I recommend redoing the analyses with higher SWE uncertainty (see Major Comment #1). This should fit nicely with what the authors have already done in exploring the impact of the SSA uncertainty.

All other aspects of the analysis are really nicely described; the manuscript does a nice job dealing with the issues of both SSA bias and setting the SSA uncertainty too low, linking these in with model simulations specifically adapted for Arctic environment: this is a critical aspect of solving the SWE retrieval problem, and presents a significant advance over other recent efforts. Adding some analysis with more realistic SWE uncertainty will help to provide the context needed to understand the results shown here.

The authors would like to thank Dr. Durand for the positive, constructive and thorough review. All of the major/minor comments have been address below. Along with comments from reviewer #1, they significantly improved the quality of the

manuscript. In particular, the data methods and discussions sections were significantly improved. We also took note of the confusion in many aspects of the manuscript. We clarified many points and did extra tests, not shown in the manuscript, which greatly improve the comprehension of the study and analysis.

1.2 Major comments

1. The configuration of the SWE uncertainty in the SVS-2 model simulation ensemble and its impact on the results needs to be further discussed. The model is run in a "point" simulation mode, and the resulting ensemble of 120 members (sometimes down-selected to 30 members) is used to configure the prior. This ensemble is from a previous study (Woolley et al. 2024). The ensemble-derived prior is then applied to retrieve SWE at multiple spatial locations, but as far as I can tell, the total SWE simulated in the model is far too precise an estimate when applied as a prior in these various locations. The prior uncertainty appears to be shown in the width of the red rectangles in Figures 7-9; so in Figure 7a, e.g., the prior uncertainty appears to be 10 mm or less; Fig 7b it appears to be 5 mm, on the order of 5-10%. The uncertainty for the other experiments is similar. While the study does not quantify the spatial variability of snowpack SWE, in situ SWE appears (in e.g. Fig 7a) to range from around 60 mm to around 125 mm. Since this SWE from the simulation is being applied as a prior on each location, the uncertainty in simulated SWE should really be closer to the snowpit SWE spatial variability, so 50 mm (or more if you allow for bias). So, using the ensemble as an estimate of the SWE at these snowpits represents an almost order of magnitude mis-match in the uncertainty (∼5-10 mm vs ∼50 mm). This mis-match can have significant implications on the validity of the retrieval - basically the retrieval is implicitly assuming the prior estimates of SWE are already known to a high degree of precision. The fact that the SWE priors are not explicit, but rather represented as layer thickness and density can be navigated by increasing the respective uncertainties to make the resulting SWE uncertainty closer to the snowpit SWE standard deviation. In summary, I think it's key to address this issue needs to be addressed head-on in the paper, and to include an additional experiment (or revising one of the other experiments) with this increase to SWE uncertainty.

We agree with the reviewer that this needs to be clarified. Since the priors used in the MCMC model are thickness and density for the two layers, what is represented in Figure 8 to 10 (Figure numbering changed due to additional Figure) is not the uncertainty in the prior used in the MCMC model but the variability in simulated bulk SWE by SVS-2. The authors kept the figures as is, but clarified this point since it shows that MCMC can generate much more variability than SVS-2 in bulk SWE, which is expected given the different spatial scales at which the model and radar measurements. The uncertainty on SWE "prior" is represented in Figure 11 where we have an uncertainty closer to 30 mm. Some of this was already discussed in Section 5 but we have done further tests where we increased the uncertainty on both thickness and density individually and at the same time. These tests are not shown in the manuscript to avoid adding confusion and too much information but additional information from those tests was added to the discussion. We have seen that the retrieval is very sensitive to thickness, where a small change in thickness can compensate for a big difference in density or SSA, thus fitting the observed backscatter but, in this case where SSA and density is underestimated, SWE is also underestimated by reducing thickness of both layers to

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55 compensate for the high volume scattering from low SSA values.

Results: Figure 6 shows the same distributions for snow water equivalent (SWE). We see that Canadian Soil Vegetation Snow version 2 (SVS-2) tends to overestimate SWE for the rounded grains (R) layer and overestimate SWE for the depth hoar (DH) layer. Variability in modelled layered SWE for both versions of SVS-2 is similar to what is observed in the field. This results in a very narrow range of modelled bulk SWE that fit very well with the observations. This tends to indicate that SVS-2 reproduces

60 *the bulk SWE properly over Trail Valley Creek (TVC) but has more difficulty in properly representing proper SWE stratigraphy. Figure 6c also shows that the higher uncertainties and the over- and underestimations of the layered SWE tend to cancel out for the bulk properties. It should be noted that the distributions in Figure 6c do not realistically represent the priors and the uncertainty on SWE since SWE is not an explicit variable used in the Markov Chain Monte Carlo (MCMC) model.*

Discussion: These results confirm that synthetic aperture radar (SAR) radar backscatter (σ^0) is sensitive to SWE in the Ku-Band

65 *range, since, even with a poorly estimated microstructure (Figures 11 a and c), which is an important parameter that drives snow volume scattering in that frequency range (Montpetit et al., 2024; Picard et al., 2022; King et al., 2018), other variables like thickness are tuned to fit the measured σ^0 (Figure 11 c), and can still achieve a reasonable SWE estimate compared to measurements. It should be noted that when SWE is poorly estimated by the prior, the posterior SWE estimate has a higher error (Figure 9), where SWE estimates are concentrated around the initial modelled SWE and do not diverge from that initial*

70 *estimate. Also, further tests were done (not shown), where the uncertainty on the SWE was increased, by increasing uncertainty on thickness and density individually and separately. Every tests resulted in underestimation of SWE, most likely due to the underestimation of Specific Surface Area (SSA) in the priors, which boosted the volume scattering of both layers. The most sensitive parameter in the MCMC model being thickness, it reduced the snow thickness to reduce the volume scattering and fit the modelled σ^0 with the measured σ^0, resulting in an underestimation of SWE. [...] A way to potentially solve the issue of the*

75 *high sensitivity to layer thickness would be to use SWE as a prior directly and infer snow density and thickness from published relationships between SSA and density (Domine et al., 2007). This will be further tested in future experiments in the context of Terrestrial Snow Mass Mission (TSMM).*

2. It is really remarkable that there is so little variability among the SWE retrievals. Fig 7a shows that all the retrievals except one seem to fall in a range of 75±5 mm, when the snowpits range from 60 to 125 mm. At first glance, this appears to be

80 totally expected, and a result of having the SWE uncertainty set so low: if you start with a prior SWE that's known to within 5 %, you're not likely to change that very much, regardless of the measured backscatter value. However, Fig 7a also shows that the retrieval is adjusts fairly significantly, moving down from ∼90 mm to 75 mm. Other experiments show less change in the average retrieved SWE (the Arctic SVS-2, the top 30 ensemble members, the increased SSA uncertainty, and the multiple observation angles), but across all six experiments (Fig 7a, 7b, 8a, 8b, 9a, 9b) there is almost no variability across the retrieved

85 SWE values. Is this due to lack of variability in the observed backscatter? Does the retrieved soil properties from Montpetit et al. 2024 play a role? Please discuss some possible reasons for this lack of much variability among the retrievals in the manuscript.

It is difficult to speak of "SWE prior" when discussing this experiment since SWE is not an explicit variable in MCMC. That said, we acknowledge the confusion coming from the red shaded area of Figure 8 to 10, and this has been clarified. The "SWE prior" uncertainty is more of the order of 30 mm (30 %)First, we believe the lack of variability comes from the small sensitivity to density and the very high sensitivity to thickness. This results in MCMC adapting thickness and SSA which are the most sensitive parameters to the radar measurements. It is possible that the extra backscatter measurements at the different incidence angles do not introduce considerably more sensitivity to SWE, and this is why TSMM is planning an additional higher frequency Ku-Band measurement, which will be more sensitive to SWE and volume scattering. This is now further discussed in the discussion section with the additional tests that were conducted. Second, in Montpetit et al. (2024), it is shown that adapting the soil properties to different land cover types does improve error between simulated and measured backscatter, but it should not have a considerable impact on the SWE retrieval using MCMC since the uncertainty in the radar backscatter (previously σ, now δ in the revised manuscript) are equal or higher to the improvement of the error when considering a single set of soil properties. This has been added to the discussion.

This result also shows that, even though the lower Ku-Band frequency (13.5 GHz) is sensitive to SWE and snow volume scattering, it still has a high sensitivity to surface scattering at the soil-snow interface, which could explain why there is not significant spread among the retrieved SWE. The lack of spread in the retrieved SWE can also be explained by the low uncertainty on the thickness priors of both layers, which are the most sensitive parameters in the MCMC model, but are restrained to a narrow range of thickness values. Also, the fact that volume scattering is less impacted by density, than it is by SSA, reduces the potential of sampling a wider range of SWE values, which is a function of snow thickness and density.

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1.3 Minor comments

1. Line 64: Please add that for these Bayesian methods, it's key to correctly specify the SWE uncertainty, which in prior studies was done by specifying layer thickness and density uncertainties.

A sentence was added to mention this:

It is key for these methods to correctly specify SWE uncertainty, where it was achieved by specifying layer and density uncertainties.

2.Line 92, Figure 1: Please comment on the difference in backscatter between the two images. Presumably these are made at different incident angles? At first blush, it looks as if nearly the same scene produced significantly different backscatter, so may need some additional discussion.

More details is now given in the text with regards to the SAR mosaic in the background. As the reviewer mentions, the image was done by overlapping two different airborne passes in the same direction, i.e. the far range of the first image meets the near range of the second :

The radar image in Figure 1 consists in a mosaic of two different airborne passes, flown in the same direction, acquired by the University of Massachusetts (UMASS) radar system (Section 2.1), where the near range acquisitions (higher backscatter) of the first pass, done at steeper incidence angles, meets the far range acquisitions (lower backscatter) of the second pass, made at shallower incidence angles.

3.Line 92, Figure 1: the combination of using a point-scale SVS-2 simulation and the reference to the Canadian High Resolution Deterministic Prediction System were a little confusing. I thought at first that CHRDPS was used in the modeling setup. I recommend just removing that grid and mention of CHRDPS if that data is not used in the study

This has been removed. Along with the comments from reviewer #1, the figure has been updated and the legend now reads:

Figure 1. Sites sampled during the January campaign of the TVC 2018/19 experiment. Squares correspond to a 100 m x 100 m around the central surveyed snowpit (see Section 2.2). Background images are two overlapped UMASS Ku-Band radar images corresponding to two different flight passes acquired November 14, 2018 (left, Siqueira et al., 2021), the 2 m ArcticDEM (center, Porter et al., 2023), and the vegetation classification (right, Grünberg and Boike, 2019).

4.Clarify what "top 30" means in methods, the first time it's introduced (line 233) not in results (line 330). Is this derived to be different for each snowpit, or is it the same 30 for all snowpits? Is it based only on SWE, or on SWE and SSA or other properties? Is it e.g. the 30 SWE values closest to the true average snowpit SWE, e.g.?

Yes, some key elements of the SVS-2 ensembles were missing from Section 2.3. To clarify what the "top 30" means, this was added in Section 2.3:

Test were also conducted in this study with the 30 ensemble members that had the best continuous ranked probability score (CRPS, see Woolley et al., 2024)

5.Line 226: Please note that when deriving SWE priors from the ensemble, the resulting prior SWE uncertainty is important, and cannot be directly obtained from the model ensemble estimates of layer thickness and density uncertainty, due to possible ensemble correlations of these quantities.

This is absolutely true. The re shaded areas shown in Figures 7 to 9 represent the variability in modelled bulk SWE by the different SVS-2 version. This variability does not translate into the uncertainty that was given in the MCMC model. Figure 6 shows how bulk SWE is not that variable in its outputs but the layered SWE is. When looking at Figure 11, it is clear that the prior uncertainty on SWE is much larger than the modelled SWE variability. The authors preferred to keep the modelled variability in Figures 8 to 10 since it shows that MCMC can reproduce a lot more variability than SVS-2, which is expected. Nonetheless, this has been clarified in the figure legend and additional text was added in the discussion.

The red shaded areas show the 1st and 3rd quartiles of the SVS-2 distributions (Figure 6c).

6.Line 237, Table 1: Please add the SWE ensemble standard deviation and mean values here.

Values were added to Table 1.

7.Line 245: Define all symbols in equation 1. Should also note the confusing aspect of σ being used to represent both uncertainty, and backscatter.

The symbols are now all defined and σ for uncertainty was modified for δ throughout the text.

[...]

$$l(\sigma^0_{mes}, \delta | \sigma^0_{sim}) = -\frac{1}{2}\left(\frac{\sigma^0_{mes} - \sigma^0_{sim}}{\sigma}\right)^2 - \ln(\sqrt{2\pi}) - \ln(\delta) \tag{1}$$

where $l(\sigma^0_{mes}, \delta | \sigma^0_{sim})$ is the likelihood metric between the measured σ^0 (σ^0_{mes}) and simulated σ^0 (σ^0_{sim}), given an uncertainty on the measured σ^0 (δ).

8.Line 278, Figures 3, 4 and 5. Calling the red line the "posterior" is sure to create confusion, as "posterior" is usually meant to be an output of the retrieval, and this is a normal distribution with mean and standard deviation derived from the snowpits

This was changed to "Snowpits" as in Figure 11.

9.Line 280, section 4.1: it is critical to provide the basic statistical summaries of the snowpit SWE. How variable was the SWE? This must be quantified, given the study objectives.

An extra figure was made for SWE (see Figure 6) with additional text to describe the SWE variability.
Figure 6 shows the same distributions for SWE. We see that SVS-2 tends to overestimate SWE for the R layer and overestimate SWE for the DH layer. Variability in modelled layered SWE for both versions of SVS-2 is similar to what is observed in the field. This results in a very narrow range of modelled bulk SWE that fit very well with the observations. This tends to indicate that SVS-2 reproduces the bulk SWE properly over TVC but has more difficulty in properly representing proper SWE stratigraphy.

Figure 6c also shows that the higher uncertainties and the over- and underestimations of the layered SWE tend to cancel out for the bulk properties. It should be noted that the distributions in Figure 6c do not realistically represent the priors and the uncertainty on SWE since SWE is not an explicit variable used in the MCMC model.

10.Line 280, section 4.1: it is critical to provide the statistical summary of the simulated SWE. This can't be easily retrieved from the depth and density histograms, because they may be cross-correlated. The little red boxes in Figure 7-9 do not provide enough quantitative information, given that the paper is aimed at SWE accuracy.

Yes, similarly to previous comment, more description on SWE variability was added in Section 4.1.
Figure 6 shows the same distributions for SWE. We see that SVS-2 tends to overestimate SWE for the R layer and overestimate SWE for the DH layer. Variability in modelled layered SWE for both versions of SVS-2 is similar to what is observed in the field. This results in a very narrow range of modelled bulk SWE that fit very well with the observations. This tends to indicate that SVS-2 reproduces the bulk SWE properly over TVC but has more difficulty in properly representing proper SWE stratigraphy. Figure 6c also shows that the higher uncertainties and the over- and underestimations of the layered SWE tend to cancel out for the bulk properties. It should be noted that the distributions in Figure 6c do not realistically represent the priors and the uncertainty on SWE since SWE is not an explicit variable used in the MCMC model.

11.Line 280, section 4.1: From comparing the various figures, it looks as if the simulation underestimates total depth, and overestimates total density, and ends up with a slight bias in SWE. Please comment on this and clarify these biases

SVS-2 tends to underestimate density for both layers for a total underestimation of bulk density. SVS-2 overestimates thickness of the rounded grain layer (R) but underestimates the depth hoar thickness. SVS-2 slightly overestimates the total thickness. This results in a very good estimations of bulk SWE but a closer look shows an underestimation of the SWE from the DH layer and an overestimation of the SWE for the R layer.
We see that SVS-2 tends to overestimate SWE for the R layer and overestimate SWE for the DH layer. Variability in modelled layered SWE for both versions of SVS-2 is similar to what is observed in the field. This results in a very narrow range of modelled bulk SWE that fit very well with the observations. This tends to indicate that SVS-2 reproduces the bulk SWE properly over TVC but has more difficulty in properly representing proper SWE stratigraphy.

12.Line 280, section 4.1: Please directly compare the measured snowpit SWE and the ensemble SWE, and discuss implications of SWE uncertainty estimation on the retrieved SWE.

New figure added for layered and bulk SWE, with description in Section 4.1 and added discussion in Section 5.2.
Figure 6 shows the same distributions for SWE. We see that SVS-2 tends to overestimate SWE for the R layer and overestimate SWE for the DH layer. Variability in modelled layered SWE for both versions of SVS-2 is similar to what is observed in the field. This results in a very narrow range of modelled bulk SWE that fit very well with the observations. This tends to indicate that SVS-2 reproduces the bulk SWE properly over TVC but has more difficulty in properly representing proper SWE stratigraphy.

Figure 6c also shows that the higher uncertainties and the over- and underestimations of the layered SWE tend to cancel out for the bulk properties. It should be noted that the distributions in Figure 6c do not realistically represent the priors and the uncertainty on SWE since SWE is not an explicit variable used in the MCMC model.

13. Line 315, Figure 7: To me, it looks like the basic result that the high bias in SSA leads to an underestimation of scattering which then leads the retrievals to bias the SWE low (Fig 7a). However, this bias does not persist in all other scenarios; the Arctic adapted SVS-2 has less bias in SSA and leads to less bias in SWE. It would be nice to comment further on this.

That is correct. The bias in SVS-2 SSA is discussed in Section 5.1 as a current limitation of SVS-2, but additional text was added with regards to bias in SSA (underestimation) leading to an overestimation of volume scattering, which results in an underestimation of SWE since MCMC reduces the thickness of each layer to account for too much scattering from the grain size.

Also, further tests were done (not shown), where the uncertainty on the SWE was increased, by increasing uncertainty on thickness and density individually and separately. Every tests resulted in underestimation of SWE, most likely due to the underestimation of SSA in the priors, which boosted the volume scattering of both layers. The most sensitive parameter in the MCMC model being thickness, it reduced the snow thickness to reduce the volume scattering and fit the modelled σ^0 with the measured σ^0, resulting in an underestimation of SWE.

14. Line 315, Figure 7, 8, 9: the error bars on the measurements are confusing. In this context, error bars like this imply an uncertainty in the measured value at the snowpit. However, if I understand, these are taken as the spatial variability of the measured values, which I don't think is the same as the uncertainty. The uncertainty is how accurately you think you measured SWE at each place, whereas spatial variability is how much SWE varies from place to place. Please derive a reasonable SWE uncertainty and change the error bars

It is true that the error bars are related to spatial variability of SWE. In this context, the spatial variability within a 100 m footprint of the radar measurements, for a given site, is considered part of the snow measurements uncertainty. This is why those error bars are there. Other metrics of uncertainty could be considered for these error bars like measurement uncertainty and vertical variability within the different Snow Micropenetrometer profiles taken but the spatial variability is considered here to have the highest impact on measured radar backscatter. Also, since the spatial variability within the radar footprint is not always best represented by a normal distribution, the error bars represent the quartile deviation (Q1 and Q3).

15. Line 315, Figure 7, 8 9: the error bars on the model seems to have been drawn wrong on figure a? The dashed line appears at the bottom of the shaded area, but I think the dashed line should be in the middle of the shaded box?

The shaded boxes were modified in Figures 8 to 10 to better represent the SVS-2 SWE uncertainty used in the MCMC model. That said, the shaded box represent the quartile deviation (Q1 and Q3). Since the SVS-2 SWE distribution is skewed, the

dashed line is not centred in the shaded area.

245 16.Line 320: It's unclear what SWE uncertainty means in this context. Is this derived from the Markov Chains? It almost reads as if this quantity is being calculated across the retrievals at the various snowpits, but that is spatial variability rather than uncertainty, which is not the same thing. If uncertainty were calculated at each snowpit, then you'd have a different uncertainty for each snowpit, as you ought, and so the Table 2 could summarize the average uncertainty, which may be what is there; but in any case, please clarify!

250 The uncertainty metric used for the retrieved and measured SWE is the quartile deviation rather than the usual standard deviation. This is due to the fact that the posterior distributions from MCMC are not all normal distributions and are often skewed. The quartile deviation is better suited to estimate the retrieved uncertainty. Values in Table 2 consist in the mean uncertainty over all sites. This has been clarified in the text and table legend.
Uncertainty is defined as the quartile deviation, and the values consist in the mean value over all sites.

255 17.Line 350, comparing Figure 8 vs Figure 9: why don't the error bars look the same here? In Figure 8a, the default SVS-2 looks much wider than Figure 8b. But as I read the paper, this shouldn't change when we go to Figure 9, correct? But Figure 9 looks much smaller?

The SVS-2 uncertainty is represented by the red shaded area. Figure 9b, 10a and 10b all have the same prior, the Top 30 Arctic version, where as Figure 9a uses the Top 30 Default version. Thus the shaded area is different between Figure 9a and all other
260 figures, which have the same shaded areas.

18.Line 360: I found Figure 10 a bit confusing. So this is at a single pit? In that case, the snowpits pdf is not a reasonable thing to show, right? Why not just show the observation at that particular pit? Same comment in Figure 11, why not show the measured value rather than the median over all pits? Those are not very relevant except this one. Similarly, the text refers to
265 bias which is usually an average over many error samples. But in this case, you should just have one error, which is equal to the estimate of each quantity from the MCMC and the measured value.

This has been clarified in Section 2.2. Was is shown is the distribution of measurements for a given site which consists in a 100 m x 100 m footprint (20 profiles total between SMP and reference snowpit).
All profiles (snowpits, SMP and MagnaProbe profiles) per site are then used to generate a statistical representation of snow
270 *conditions within the radar footprint, with a measured snow uncertainty represented by the spatial variability within the footprint. Spatial variability consists in the largest uncertainty within the footprint compared to snow parameter measurement uncertainty, the latter can thus be neglected.*

19.Line 373: What do min and max values mean for each iteration in Figure 11?

The min/max values for each iteration is the min/max values sampled across the seven parallel chains. This has been clarified
275 in Figure legend:

*Full horizontal lines consist in median values from measurements (snowpits) and the dashed horizontal lines consist in the
mean of the priors. The min/max values consist in the minimum and maximum properties sampled at each iteration between
the seven parallel sampling chains.*

20.Line 373: Please show the prior values in Figure 11.

280 Prior values were added to the figure as a dashed line.

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