

## Initial Author Response for “Simulating snow properties and Ku-band backscatter across the forest-tundra ecotone”, Woolley et al.

The authors would like to thank the editor and Reviewer 1 and 2 for the time taken to provide the detailed and thorough reviews. Our responses are in blue, modified text that we will add to the revised document in italics and reviewer comments are in black.

### Answer to Reviewer 1:

The study compares simulated snow parameters using SVS2-Crocus to in situ measurements at a study area in the NWT, Canada. Two versions of the model are applied; the default model and an Arctic-specific modification. Several locations with differing vegetation and snow conditions are analyzed. Furthermore, a forward model is used to simulate microwave backscatter from SVS2-Crocus outputs, comparing these to backscatter simulations using the in situ data directly. A microwave-effective snowpack concept, which aggregates the data to three representative layers, is used. The paper is of interest to the scientific community as it has become clear that some type of fusion of modelled and remote sensing information is required for successful retrieval of SWE from spaceborne radar. This concerns, in particular, approaches using Ku-band SAR backscatter. This paper takes some steps to attempt to quantify how an advanced coupled land-surface -snow process model reproduces natural snowpacks in a challenging environment, and what are the implications on (simulated) backscatter. As such, the study is worthy to consider for publication.

We thank the reviewer for their comments and are pleased that the study is considered suitable for publication.

The study is also generally well written although some specifics in the methodology are hard to grasp and require several readings. For example, from the abstract it was not at first obvious that actual observations of backscatter are not used, only simulations. Furthermore, it is hard to discern where exactly the three layer aggregates (radar equivalent snowpack) were used: in simulations based on SVS2-Crocus, in simulations from snowpit data, or perhaps both? Terminology referring to the sites also changes occasionally, sometimes referring to the biome (tundra, forest), sometimes to the names defined in Figure 1. These are the main examples, but the complexity of the diverse model settings makes the paper somewhat hard to follow and requires particular care in describing the experimental setups.

We thank the reviewer for these constructive comments and for highlighting the need for greater clarity in the description of the methods. We will revise the manuscript accordingly to improve the clarity and consistency:

Abstract: We will revise the abstract to explicitly state that no radar backscatter observations are used in this study, and that all results are based on forward simulations using the SMRT model. The following modified text will be added to the manuscript abstract:

*‘Simulated backscatter from multi-layer (~20-layer) SVS2-Crocus snowpack simulations and simplified 3-layer ‘radar-equivalent’ SVS2-Crocus simulations were compared to simulated backscatter from snow pit observations (with no snow layer simplification).’*

45 Methods: We will clarify when the 3-layer ‘radar-equivalent’ snowpack configuration was applied to our simulations. The simplified configuration was only used for the SVS2-Crocus driven simulations, while the snow pit-driven simulations retained the full detailed measured stratigraphy. The following text will be added to the last paragraph of the introduction within the manuscript:

50 *‘The impact of an ensemble of simulated snow properties on Ku-band (13.5 GHz) backscatter using the Snow Microwave Radiative Transfer Model (SMRT; Picard et al., 2018), is then tested under three configurations:*

1. *SMRT driven by a detailed (~20-layer) SVS2-Crocus simulated snowpack.*
2. *SMRT driven by a simplified (3-layer) radar-equivalent SVS2-Crocus simulated snowpack, following the approach of Meloche et al., 2025.*
- 55 3. *SMRT driven by raw snow pit observations, representing the best available measured representation of the snowpack and serving as a reference for assessing model performance.’*

60 Terminology: We will revise throughout the manuscript the text to ensure consistent references to site names and vegetation types. We will refer to all sites by their individual names, as described in Figure 1. These are:

- Upper Plateau
- Trail Valley Creek
- 65 • Valley
- Small Shrub
- Mixed Shrub
- Shrub Tree
- Havikpak

70 However, in section 4.2 (Profiles of density and SSA), we perform statistical analysis on groups of sites defined by their vegetation types, as outlined in Figure 1. This grouping is also clarified on Section 3.2.1 of the manuscript. The site groups are as follows:

- Tundra (Upper Plateau and Trail Valley Creek)
- Deciduous Shrub (Valley, Small Shrub and Mixed Shrub)
- 75 • Forest (Shrub Tree and Havikpak)

Further details of how this is modified in the manuscript can be found on Line 180 of this document.

My main concern, however, is related to the usefulness of the backscatter simulation setup itself. The SMRT model is treated as a black box, testing which kind of numbers come out with each version of the input data. It seems that the pit data forcing is used as the “truth”, with SVS2-Crocus -based simulations representing deviations (“errors”) from this. No real effort is placed on which parameters actually induce these differences, beyond testing different approaches for tuning the optical grain size/SSA. Since the study is based on only simulated backscatter, one could expect a thorough sensitivity study on different parameters, or something similar. Perhaps using the 120 ensemble members in SVS2-Crocus makes this a challenge; however, you could then consider dropping the ensemble approach, and use individual, controlled simulations?

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90 The primary objective of this study was to investigate uncertainty in snowpack modelling  
and its effect on snow backscatter simulations. Recognising the known uncertainties in  
the simulation of SSA and density by detailed snowpack models in the Arctic (Woolley et  
al., 2024; Royer et al., 2021; Domine et al., 2019), we chose to focus on the impact on  
backscatter simulations using SMRT as this is the primary objective of our study. Given  
95 the wide range of possible SMRT parameter combinations and model options (Sandells  
et al., 2024), we adopt the configuration constrained by Montpetit et al., 2024 at Trail  
Valley Creek. The configuration was considered suitable for our simulations, as it was  
specifically optimised for the tundra snow conditions at TVC through the calibration of  
microstructural (e.g. correlation length, microstructure model) and radiative (e.g. soil  
100 permittivity, roughness) parameters against field snow pit and radiometric observations  
and validated through Ku-band backscatter simulations using airborne SAR data. The  
same approach has been applied in related studies (e.g. Meloche et al., 2025; Montpetit  
et al., 2025).

By adopting this configuration, we were able to isolate the influence of snow model  
uncertainty on simulated snow backscatter. Our focus is therefore on quantifying and  
understanding the implications of snow model uncertainty, which can be effectively  
105 investigated using the approach established by Montpetit et al., 2024. Expanding the  
analysis to include SMRT parameter sensitivities at this stage would dilute the primary  
objective of the study.

To clarify this in the manuscript, we will add the following text to section 3.2.2, SMRT:

110 *'We adopt the configuration constrained by Montpetit et al., 2024 as it was  
specifically optimised for the tundra snow conditions at Trail Valley Creek through  
the calibration of microstructural and radiative parameters against field snow pit  
and radiometric observations and validated through Ku-band backscatter  
simulations using airborne SAR data. By adopting this configuration, we were able  
to isolate the influence of snow model uncertainty on simulated snow backscatter.'*

115 Further, some confusion is created by first choosing to fix a scaling parameter in the  
forward model (the polydispersity factor  $K$ ) at unity, only to re-introduce another scaling  
parameter with basically the same end result, as adjusting  $K$  would have had. I realized  
only after some time that the idea is to try to scale the SVS2-Crocus SSA to observations;  
however, the choice of the scaling factors tested seems arbitrary. Of some interest could  
120 be to try to derive your own optimal scaling for 1) SSA 2) density 3) possibly another  
parameter, such as snow depth, and with the (average) optical scaling reconstruct the  
simulation exercise.

We thank the reviewer for this constructive suggestion. The scaling factor from Brucker et  
al., 2011 was originally selected because it is one of the few documented values directly  
125 applied to Crocus model output and microwave simulations. The value represents a  
vertically averaged adjustment intended to capture differences between wind slab and  
depth hoar snow types. We also adopted this value to limit the risk of overfitting our  
simulated output to field data.

That said, we acknowledge the uncertainties associated with applying this factor within  
our study. Considering the reviewers comments, we have reconsidered this approach.  
130 Rather than relying on the fixed value of 0.63, we have removed this step from our  
evaluation. Instead, we focus on the role of SSA and density (Fig. 8, 9e & 9f), as these

snowpack properties are key contributors the backscatter simulations in SMRT, and they determine the exponential correlation length that governs scattering behaviour.

135 We outline in detail on Line 246 of this document how we will modify the manuscript to account for the removal of the 0.63 scaling factor.

Please see major comments below for specifics.

Major comments

140 Abstract: by reading only the abstract, it is not fully clear that you do not actually use observations of backscatter: “Modelled backscatter...were compared to backscatter using...” please make it more explicit from the start that this is a simulation exercise.

We will change the text to:

145 *‘Simulated backscatter from multi-layer (~20-layer) SVS2-Crocus snowpack simulations and simplified 3-layer ‘radar equivalent snowpack’ SVS2-Crocus simulations were compared to simulated backscatter from snow pit observations (with no snow layer simplification).’*

150 In Abstract, line 25: “leading to high errors...” this is misleading again, as an “error” in simulated backscatter implies you have measured the actual one. Rather, this is a root-mean-square difference between two simulations with different model forcing. I would suggest to change the terminology throughout the manuscript, also changing RMSE(rror) to RMSD(eviation)

We agree with the reviewer and will change the terminology throughout the manuscript to RMSD(eviation) to reflect that we are presenting differences.

Introduction: this section is very nicely written

155 We thank the reviewer for this positive comment.

...except that in the last sentence, you should already make clear which (Crocus outputs, field data, or both) are converted from multi-layer to the radar-equivalent 3-layer setup. Now this is not clear at all.

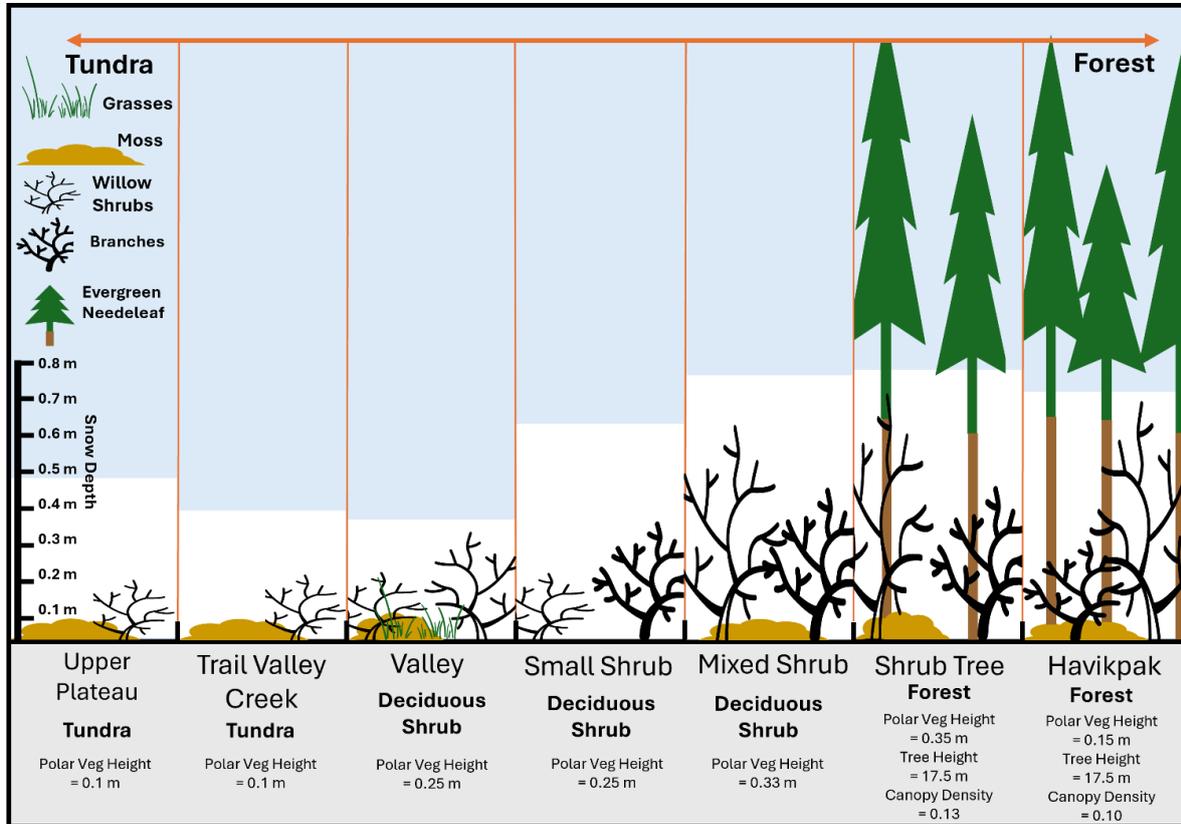
We will revise the last sentence of the introduction to provide more clarity:

160 *‘The impact of an ensemble of simulated snow properties on Ku-band (13.5 GHz) backscatter using the Snow Microwave Radiative Transfer Model (SMRT; Picard et al., 2018), is then tested under three configurations:*

- 165
4. *SMRT driven by a detailed (~20-layer) SVS2-Crocus simulated snowpack.*
  5. *SMRT driven by a simplified (3-layer) radar-equivalent SVS2-Crocus simulated snowpack, following the approach of Meloche et al., 2025.*
  6. *SMRT driven by raw snow pit observations, representing the best available measured representation of the snowpack and serving as a reference for assessing model performance.’*

170 Figure 1 is very good and informative. However, can you add a scale for the snow depths? I guess the average snow depth can be indicated just as easily as the relative depth?

We agree with the reviewer's suggestion and will include a scale bar in the revised figure as follows.



175 **Figure 1:** Schematic showing the variation in vegetation and relative snow depth (white bars) across a 40-km transect of the Northwest Territories, Canada (Fig. 2). SVS2-Crocus model parameters of vegetation type, polar vegetation height (see section 3.2.1 for definition), tree height and canopy density are also displayed for each site.

Throughout the paper, please choose which name you use when referring to sites. Now, sometimes “forested sites” and “tundra” are used, sometimes “Havikpak” etc. You could also use always both to be explicit e.g. “Upper plateau (tundra)”

180 We thank the reviewer for pointing out this inconsistency. We will refer to all sites by their individual names, as described in Figure 1. These are:

- Upper Plateau
- Trail Valley Creek
- Valley
- Small Shrub
- Mixed Shrub
- Shrub Tree
- Havikpak

185  
190 However, in section 4.2 (Profiles of density and SSA), we perform statistical analysis on groups of sites defined by their vegetation types, as outlined in Figure 1. This grouping is also clarified in Section 3.2.1 of the manuscript. The site groups are as follows:

- Tundra (Upper Plateau and Trail Valley Creek)
- Deciduous Shrub (Valley, Small Shrub and Mixed Shrub)
- Forest (Shrub Tree and Havikpak)

195 We acknowledge that this distinction may not have been sufficiently clear in the original text. To address this, we will modify the first paragraph of Section 4.2 to explicitly restate the grouping and refer the reader back to Figure 1. The revised paragraph will read as follows:

200 *‘Figure 5 and 6 compare measured and simulated profiles of snow density and SSA for Upper Plateau, Small Shrub and Havikpak, representing three sites of contrasting vegetation type (see Fig. 1) for the 2021/22 and 2022/23 winter seasons, respectively. All remaining sites are displayed in Appendix B. We discuss the results from figures 5, 6, 7 and Appendix B in this section with reference to all measurements, within each vegetation type, as classified in Fig. 1: Tundra (Upper Plateau, Trail Valley Creek), Deciduous Shrub (Valley, Small Shrub, Mixed Shrub) and Forest (Shrub Tree and Havikpak). Measured profiles of snow density at tundra and deciduous shrub sites exhibit the typical structure of an Arctic snowpack: low-density basal layers ranging between  $150 \text{ kg m}^{-3}$  and  $300 \text{ kg m}^{-3}$  overlain by higher density surface layers ranging between  $300 \text{ kg m}^{-3}$  and  $400 \text{ kg m}^{-3}$  (Fig. 5 & 6, Appendix B). At forest sites, measured snow density shows less variability throughout the snowpack with surface and basal layers exhibiting similar densities (Fig. 5 & 6, Appendix B: WS Mean:  $196 \text{ kg m}^{-3}$  ; DHF Mean:  $192 \text{ kg m}^{-3}$ ). Despite differences in snow density, the pattern of measured SSA is consistent amongst all sites with lower SSA values for basal layers (ranging between  $5 \text{ m}^2 \text{ kg}^{-1}$  and  $20 \text{ m}^2 \text{ kg}^{-1}$ ) and higher SSA (ranging between  $30 \text{ m}^2 \text{ kg}^{-1}$  and  $60 \text{ m}^2 \text{ kg}^{-1}$ ) values for near-surface layers (Fig. 5 & 6, Appendix B). The variability between measured pit profiles of density and SSA decreases from tundra to forest (Fig. 5 & 6, Appendix B).’*

220 p9, eqs 1 and 2 and associated text. As pointed out in the above, it is unclear from the text why the  $K$  parameter is fixed here, while later on you choose to scale the SSA. I realize this is due to the experimental setup of comparing “simulations vs. simulations”, and this should be clearly mentioned. You should display the scaling factor you use in eq. 2 (and maybe forget about  $K$ , since essentially you do not use it).

225 In response to the reviewer’s comment, we will remove the scaling factor step (use of 0.63) from our backscatter simulations. This is explained further in our response to the reviewer’s next comment. The scaling factor is therefore not required in equations 1 and 2 and will be removed from the associated text and discussion.

230 We will, however, retain the polydispersity parameter ( $K$ ) as 1 in Equation 1. Although multiplying by 1 may appear redundant, we retain the  $K$  term because polydispersity is an evolving area of study in microwave snow modelling (Picard et al., 2022; Montpetit et al., 2024; Sandells et al., 2024). Including it explicitly allows our framework to remain consistent with emerging formulations and facilitates future model development where variable polydispersity may be incorporated. This will be clarified in the methods section of the manuscript as follows:

235 *‘The polydispersity was assumed to be 1 for all simulations. Fixing  $K = 1$  provided a consistent configuration suitable for our analysis of simulated SVS2-Crocus backscatter versus simulated pit backscatter. This assumption isolates the*

*influence of snow microstructure and density differences between SVS2-Crocus and pit measurements, while avoiding additional uncertainty introduced by varying polydispersity.'*

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I also fail to see why the scaling factor of 0.63 derived in a paper from 2011 could be relevant. I would suggest another approach: 1) derive your optimal scaling factors required to match SVS2-Crocus to field data 2) do this at least for SSA, density and snow depth 3) analyze which is the most important factor to scale (which has the largest impact) for each surface type. As an optimal case, you could test scaling all three+ parameters to match the field data, and see how much RMSD remains from variability in the ensembles.

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We thank the reviewer for this constructive suggestion. As outlined above (Line 123 of this document), the scaling factor from Brucker et al., 2011 was originally selected because it is one of the few documented values directly applied to Crocus model output applied to microwave simulations and represents a vertically averaged adjustment intended to capture differences between wind slab and depth hoar snow types. We also adopted this value to limit the risk of overfitting our simulated output to field data.

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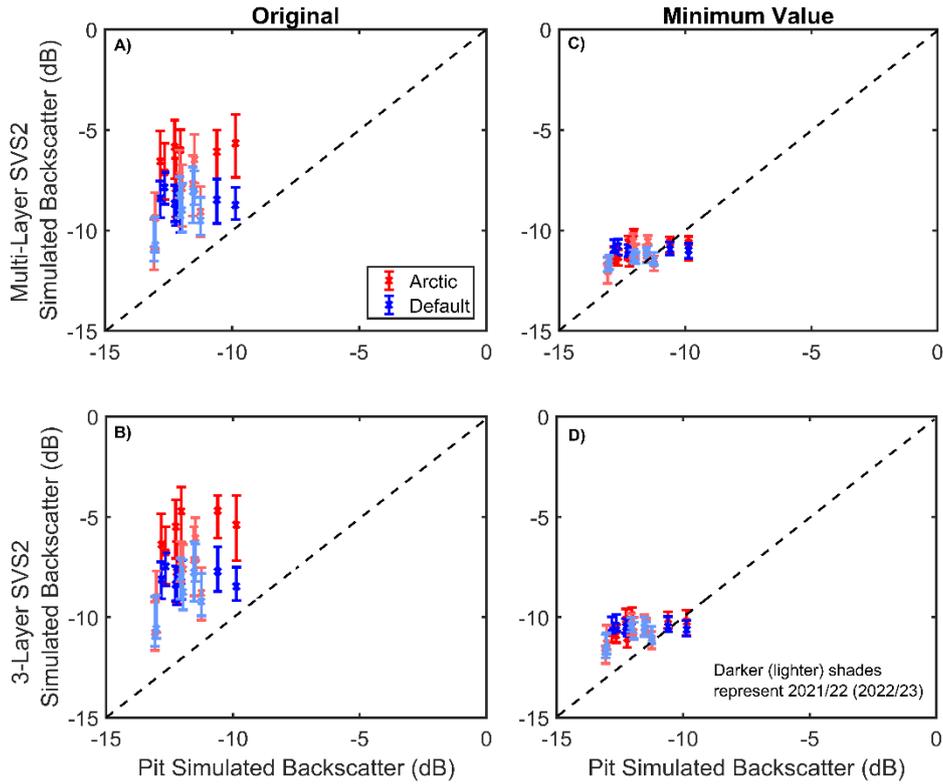
That said, we acknowledge the uncertainties associated with applying this factor within our study. Considering the reviewers comments, we have reconsidered this approach. Rather than relying on the fixed value of 0.63, we have removed this step from our evaluation. Instead, we focus on the role of SSA and density (Fig. 8, 9e & 9f), as these snowpack properties are key contributors the backscatter simulations in SMRT, and they determine the exponential correlation length that governs scattering behaviour.

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The manuscript will be revised in response to this comment as follows:

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Figure 9: Panels C and D will be removed, retaining panels A, B, E and F.



**Figure 2:** Comparison between pit simulated backscatter and SVS2-Crocus simulated backscatter for a multi-layer (A, 'Original') and 3-layer (B, 'Original') radar equivalent snowpack (interquartile range, median) for the 2021/22 and 2022/23 winter seasons at Ku-band frequency (13.5 GHz). C & D) comparison with a minimum SSA of  $8.7 \text{ m}^2 \text{ kg}^{-1}$  ('Minimum Value'; maximum optical diameter equivalent 0.75 mm).

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**Table 1:** Rows C & D will be removed, retaining rows A, B, E and F.

**Table 1:** Mean RMSD between simulated SVS2-Crocus backscatter and snowpit simulated backscatter (dB) for all seven sites for the 2021/22 and 2022/23 winter seasons. Separated for default and Arctic SVS2-Crocus. Letters refer to panels on Fig. 9.

	2022		2023	
	Arctic	Default	Arctic	Default
<b>A) SVS2 Original</b>	5.3	3.5	4.2	3.6
<b>B) 3-Layer Original</b>	5.8	3.9	4.6	3.9
<b>C) SVS2 Minimum</b>	1.3	1.4	1.6	1.5
<b>D) 3-Layer Minimum</b>	1.7	1.7	2.0	1.9

The text in section 4.3 Simulated Ku-band backscatter will be revised, to discuss only method 2, limiting the minimum SSA of the snow grains to a value of  $8.7 \text{ m}^2 \text{ kg}^{-1}$ :

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*'As the underestimation in basal SSA values simulated by both default and Arctic SVS2-Crocus strongly influence the simulation of snow backscatter, we addressed this bias by constraining the minimum SSA of the snow grains to a value of  $8.7 \text{ m}^2 \text{ kg}^{-1}$  (Fig. 9c & d). The selected value represents the average median DHF value from all pit measurements at all sites and removes the effect of unrealistically low simulated SSA values.'*

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280 *Implementing a minimum SSA value removes the influence of large snow grains on the simulation of snow backscatter and allows the simulation of a weaker backscatter that is more representative of measurements (values ranging between -10 to -12 dB). Applying a minimum SSA value also reduces the difference between default and Arctic SVS2-Crocus suggesting this method constrains a key model uncertainty that contributes towards the inaccurate simulation of snow backscatter (Fig. 9c & 9d; Table 1c). The average RMSD of all sites is reduced when applying a minimum value by 59% for default SVS2-Crocus and 67% for Arctic SVS2-Crocus for 2021/22 and 2022/23. The reduction in the RMSD for Arctic SVS2-Crocus is greater than that of default SVS2-Crocus, suggesting the improved simulated density profile contributes to the improved simulation of backscatter when the large influence of low SSA values is removed.*

290 *A radar-equivalent snowpack is able to replicate the scattering behaviour of the multi-layer snowpack, resulting in an RMSD below 1 dB (Table 1) at all sites except for Shrub Tree (RMSD: 1.32 dB) and Havikpak (RMSD: 1.30 dB) in 2022 where snowpacks are deeper and more complex than in 2023 (Fig. 4). The overestimation in simulated backscatter when compared to snow pit simulated backscatter is consistent between both multi-layer (Table 1a) and 3-layer simulations (Table 1b). Following the pattern of the multi-layer snowpack, implementing a minimum SSA values reduce the RMSD at all sites when using a radar-equivalent snowpack by 54% (default SVS2-Crocus) and 65% (Arctic SVS2-Crocus) for 2021/22 and 2022/23. The computation time in SMRT simulations was reduced by 60% by simplifying the multi-layer snowpack (~20 layers) to a radar equivalent snowpack (3 layers). The radar-equivalent snowpack can therefore increase the computational efficiency for SWE retrieval algorithms without altering the scattering behaviour.'*

305 Any reference to the 0.63 scaling factor, reducing the scattering behaviour of the snow grains with a vertically averaged scaling factor of 0.63, will be removed from the manuscript. Paragraph 2 of section 5.2, Capacity to simulate snow backscatter, will read as follows:

310 *'An improved simulation of snow backscatter can be achieved by implementing a minimum SSA value of  $8.7 \text{ m}^2 \text{ kg}^{-1}$ , reducing scattering effects of the snowpack. Implementing a minimum SSA value removes the influence of large depth hoar snow grains and constrains a key model uncertainty when simulating backscatter. Although the polydispersity value was assumed to be 1 for all simulations, a fixed value of K provided a consistent configuration suitable for our analysis of simulated SVS2-Crocus backscatter versus simulated pit backscatter. Typical polydispersity values based upon measurements in tundra snow range from 0.6 - 0.75 for rounded grains and 1.1 - 1.9 for depth hoar (Montpetit et al., 2024; Picard et al., 2022; Sandells et al., 2024), which relate to the two-layer nature of an Arctic snowpack (Derksen et al., 2014). However, few studies have applied a polydispersity parameter to simulated outputs. In typical Arctic depth hoar (polydispersity 1.1 – 1.9), this amplifies the influence of larger snow grains (low SSA/high optical diameter), increasing the exponential correlation length and the simulated microwave scattering. Consequently, instead of accounting for polydispersity in SVS2-Crocus, this analysis focuses on accurate estimation of SSA.'*

The first line of the last paragraph of the conclusion will be modified to:

325 *‘Scaling the scattering effect of snowpack microstructure by implementing a minimum SSA ( $8.7 \text{ m}^2 \text{ kg}^{-1}$ ) improved the simulation of snow backscatter at Ku-band frequency at all sites across the forest-tundra ecotone.’*

Again, it is not clear to which data the n-layer -> 3-layer conversion is applied. Apparently to SVS2-Crocus at least, but is it applied to field data as well? Or are field data always simulated “as is”?

330 The n-layer to 3-layer conversion is only applied to the SVS2-Crocus simulated data. The field data is simulated as is, using the n-layers. This gave us one set of simulated backscatter coefficients from observed snow properties that was used as a reference against which we compared simulated backscatter coefficients derived from snowpack properties simulated by SVS2-Crocus. The 3-layer simplification of the SVS2-Crocus simulated data mimics the necessary approach for operational deployment with airborne or satellite data. This is now clarified within our study aims and objectives, that have been revised at the end of the introduction section of the manuscript:

335 *‘The impact of an ensemble of simulated snow properties on Ku-band (13.5 GHz) backscatter using the Snow Microwave Radiative Transfer Model (SMRT; Picard et al., 2018), is then tested under three configurations:*

- 340 a) *SMRT driven by a detailed (~20-layer) SVS2-Crocus simulated snowpack.*  
 b) *SMRT driven by a simplified (3-layer) radar-equivalent SVS2-Crocus simulated snowpack, following the approach of Meloche et al., 2025.*  
 c) *SMRT driven by raw snow pit observations, representing the best available measured representation of the snowpack and serving as a reference for assessing model performance.’*

345 Whole section 4.0 on results. It is quite tedious to read endless RMSE values in the text, and the point is quickly lost. This really gets out of hand e.g. on p. 16. Please tabulate the results, refer in the text to the tables, highlighting only the most important results.

350 We appreciate the reviewer’s suggestion. We will summarise the key findings from Section 4 in a table and revise the corresponding text to enhance readability as follows:

**Table 2:** Mean RMSD and SS scores for measured and simulated snow density ( $\text{kg m}^{-3}$ ) and SSA ( $\text{m}^2 \text{ kg}^{-1}$ ) for combined 2021/22 and 2022/23 snow seasons. Statistics are presented for each layer (depth hoar and wind slab) and each vegetation type, as classified in Fig.1: Tundra (Upper Plateau, Trail Valley Creek), Deciduous Shrub (Valley, Small Shrub, Mixed Shrub) and Forest (Shrub Tree and Havikpak).

		Default SVS2-Crocus		Arctic SVS2-Crocus	
		Density ( $\text{kg m}^{-3}$ )			
		RSMD	SS	RSMD	SS
Wind Slab	Tundra	202	0.19	138	0.34
	Deciduous Shrub	141	0.27	97	0.54
	Forest	106	0.30	84	0.38
Depth Hoar	Tundra	72	0.62	66	0.63
	Deciduous Shrub	63	0.77	67	0.57
	Forest	71	0.71	80	0.80
		SSA ( $\text{m}^2 \text{ kg}^{-1}$ )			

		RSMD	SS	RSMD	SS
<b>Wind Slab</b>	Tundra	13	0.83	12	0.72
	Deciduous Shrub	11	0.52	11	0.52
	Forest	9	0.78	9	0.76
<b>Depth Hoar</b>	Tundra	5	0.60	6	0.93
	Deciduous Shrub	4	0.79	5	0.93
	Forest	3	1.05	4	1.16

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Figure 4: you could comment in the text that the variability of Arctic SVS2-Crocus snow depth is much reduced compared to the Default run for most sites. Why is this?

360

The reduced variability in snow depth is primarily due to the densification of the snowpack by Arctic SVS2-Crocus, where incorporating wind-induced compaction processes increase snowpack density and reduce snow depths to values more consistent with observations. In contrast, default SVS2-Crocus uses parameterisations designed for alpine snow types, which are not optimised for Arctic snowpacks and therefore produce higher variability in terms of snow density and associated snow depth. By considering the processes relevant to Arctic conditions, SVS2-Crocus produces less variable snow depth simulations. We will add a sentence to section 4.1 of the revised manuscript to comment about the reduced variability in snow depth with Arctic SVS2-Crocus:

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*'The reduced variability in snow depth simulated by Arctic SVS2-Crocus is primarily due to the inclusion of wind-induced compaction, which increases snowpack density and produces snow depths more consistent with observations compared to the default configuration.'*

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It is also not clear against which SD data the RMSEs are calculated against. Magnaprobe, pit, or both?

375

The RMSD values (updated in response to a previous review comment) are calculated using both magnaprobe and snow pit data. Snow depth was measured along the 1 km transect and in spirals around each pit at all non-forested sites, resulting in approximately 800 measurements per site. These measurements were combined with the pit data to calculate the RMSD. A sentence will be added to section 3.2.1 of the manuscript:

*'RMSD values were calculated using combined Magnaprobe transect and snow pit measurements, with Magnaprobe data serving as the primary reference.'*

380

Same question as above for SWE. are the RMSEs against Pit or SWE Tube values?

385

The RMSD values (updated in response to a previous review comment) are calculated using the aggregation of both SWE tube and snow pit measurements. At each of the three pits, we collected one SWE profile in 2021/22 and two SWE profiles in 2022/2023, which were combined with ESC-30 measurements made at approximate intervals of 50 m along each 1 km transect of snow depths.

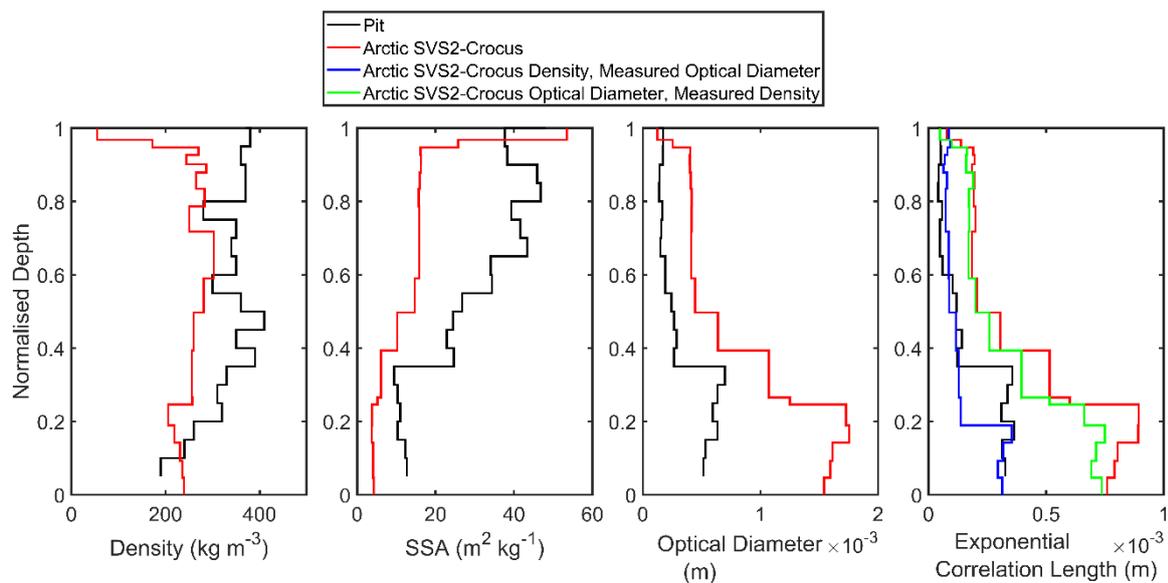
For density, can you not calculate a reference value from SWE tubes? Do you have the snow depth from the SWE core site recorded?

390 We thank the reviewer for this suggestion and agree it is possible to estimate snow density values from our SWE tube measurements. However, we only have a limited number (~20) of ESC-30 measurements available for the 2022/23 winter season, and none for the 2021/22 winter season. As a result, the temporal coverage is insufficient for robust interannual comparison. Our goal is to provide an overall view across both winters, and including the SWE-derived densities from a single season would bias the analysis towards 2022/23. Therefore, we have chosen to rely on snow pit measurements to ensure 395 consistent and representative assessment of snow density across both years.

Figure 8. The text refers to SSA, but optical grain diameter is shown. Please use one or the other.

400 Thank you for pointing out this inconsistency. We will revise figure 8 to include both SSA and the optical grain diameter. Specifically, we will present a new figure showing density, SSA, optical diameter and the exponential correlation length.

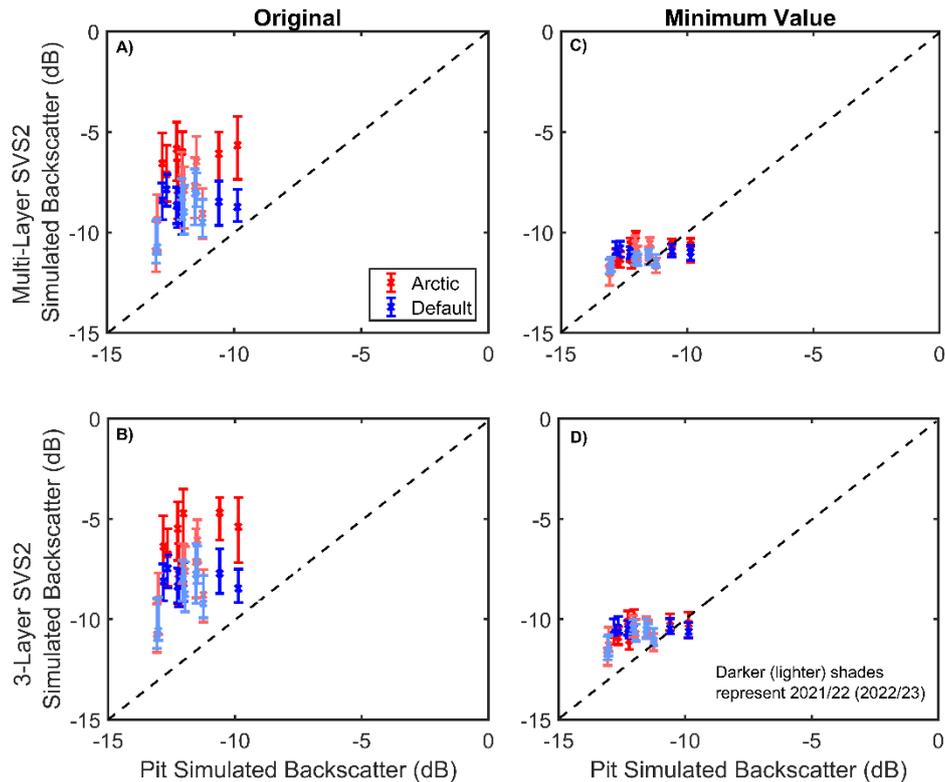
In the caption, we will reference the equation used to convert SSA into optical diameter and explain that SSA is measured in the field, while optical diameter is a direct output of Crocus (it does not compute SSA directly), hence the need to present both variables.



405 **Figure 3:** Impact of density and optical diameter on the exponential correlation length at Trail Valley Creek (2021/22) simulated by Arctic SVS2-Crocus (Eq.1). Simulated and measured SSA is also displayed. SSA is measured in the field but not computed directly by SVS2-Crocus therefore, simulated values were derived from the modelled optical diameter using:  $SSA = \frac{6}{\rho_{ice} D}$  where  $D$  is the optical diameter and  $\rho_{ice}$  is the density of pure ice ( $917 \text{ kg m}^{-3}$ ).

410 Figure 9: the figure sort of captures why applying just a random scaling factor does not tell us much. Please consider, as suggested, making equivalent scatter plots by optimally scaling different variables. This will tell you at least which parameters carry the most weight, possibly informing where future modelling efforts should focus on.

415 In response to this review comment, and a major comment by Reviewer #1, we have reconsidered our approach and will remove the scaling factor step from our evaluation. Figure 9 will therefore retain panels A, B, E and D. Panels E and D will be renamed to C and D, to account for the removal of the scaling factor.



420 **Figure 4:** Comparison between pit simulated backscatter and SVS2-Crocus simulated backscatter for a multi-layer (A, 'Original') and 3-layer (B, 'Original') radar equivalent snowpack (interquartile range, median) for the 2021/22 and 2022/23 winter seasons at Ku-band frequency (13.5 GHz). C & D) comparison with a minimum SSA of  $8.7 \text{ m}^2 \text{ kg}^{-1}$  ('Minimum Value'; maximum optical diameter equivalent 0.75 mm).

p19, lines 377-380. The two methods are already described in the Methods section, not necessary to repeat here. As indicated before, I do disagree with the usefulness of the methods.

425 We will remove these two lines from the text.

p19 line 385 "simulation of weaker backscatter that is more representative of measurements" Which measurements? This again seems to refer to measurements of backscatter.

We understand the confusion. We will change the text as follows:

430 *'simulation of weaker backscatter that is more representative of pit simulated backscatter.'*

435 p19 line 394. "A radar equivalent snowpack..." reading between the lines, I realized from this sentence that the pit data were used "as is" and the radar-equivalent approach was not applied to them. However, taken out of the context of the rest of the paper, this sentence again seems to imply that you had some backscatter measurements to compare with ("...replicate the scattering behaviour of the multi-layered snowpack"). It should be made clear throughout that you are comparing simulations with other simulations.

We will change the sentence to say, 'A simulated radar-equivalent snowpack' and ensure this is made clear throughout the entire manuscript.

440 p19 line 398 “vertically averaged scaling factor” What is this?

The vertically averaged scaling factor is 0.63 taken from Brucker et al. (2011) and represents a vertically averaged adjustment intended to capture the differences between wind slab and depth hoar snow types. However, in response to the suggestions made by the reviewer, this approach and corresponding text will be removed from the manuscript.  
445 Please see Line 246 of this document for a detailed description of how the manuscript will be modified.

Minor comments

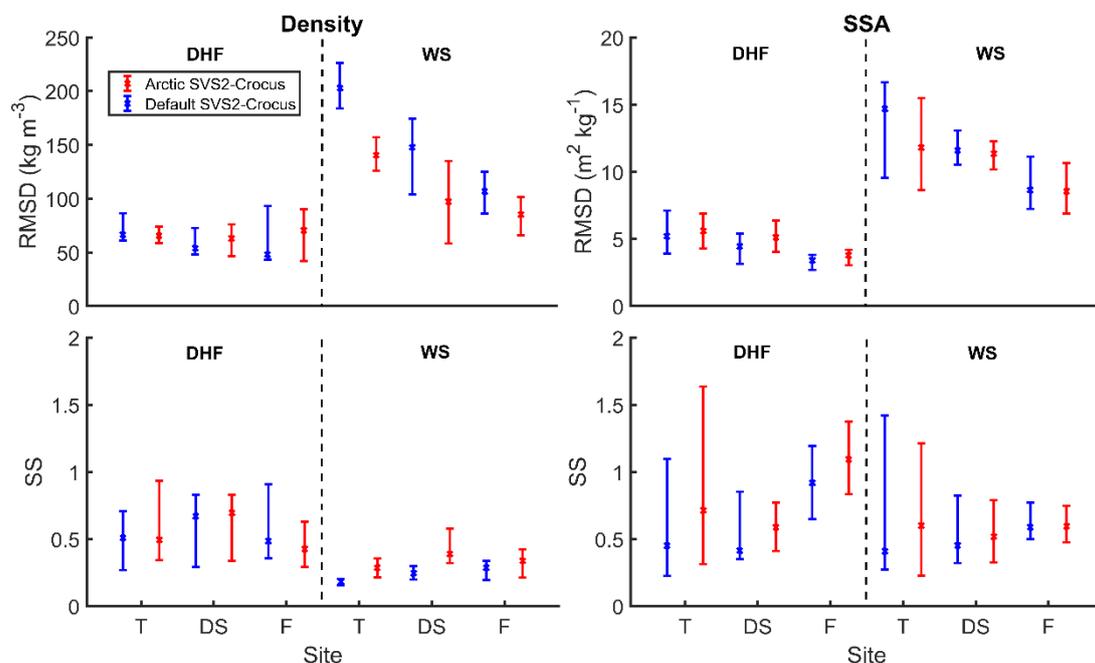
P8, line 194. Please clarify how exactly the division into WS and DHS was made (values).

We will add the following text to the manuscript:

450 *‘The DHF of each measured profile was determined by identifying transitions in the density and/or SSA. The transition between the SSA for different layers is often more distinct than density (Rutter et al., 2019), providing a sharper transition between wind slab (WS) and depth hoar that can be visibly identified. Where the transition between the snow types occurs, the density and/or SSA value is noted, cross referenced with those presented in Fig. 9 of Rutter et al. (2019) and the grain type reported during snow pit measurements.’*  
455

Figure 7: please switch the order of Arctic and Default in the panels. Logically, since default is the starting point, it should be displayed on the right (also to match Figure 4). explain acronyms WS and DHS also in the figure caption.

460 We will switch the order and explain the acronyms as Wind Slab (WS) and Depth Hoar (DHF).



**Figure 5:** RMSD and SS scores the simulation of density ( $\text{kg m}^{-3}$ ) and SSA ( $\text{m}^2 \text{kg}^{-1}$ ) by default and Arctic SVS2-Crocus for different vegetation types (T: Tundra; DS: Deciduous Shrubs; F: Forest – described in section 3.2.1) for the 2021/22 and 2022/23 field campaigns. Scores are separated for depth hoar (DHF) and wind slab (WS).

465

470 p20 line 406-407 “to assess the reliability of Ku-band backscatter SWE retrievals”. This statement may be the underlying reason of the study, but you do not really go into retrieval so it is also misleading. Please reword, e.g. “assess the reliability of forward model simulations driven by SVS2-Crocus, a crucial factor considering inversion of SWE from backscatter observations” or something similar.

We will reword the sentence to:

475 *‘Consequently, to assess the reliability of forward model simulations driven by SVS2-Crocus, which are a requirement to inform the inversion of SWE from backscatter measurements, an evaluation of simulated density and SSA by SVS2-Crocus was first conducted across the forest-tundra ecotone to quantify the uncertainties in the representation of physical snow properties.’*

p23 line 505 large grains result in increasing exponential correlation length, not the opposite.

Thank you for noticing this error. We will change the text as follows:

480 *‘However, few studies have applied a polydispersity parameter to simulated outputs. In typical Arctic depth hoar (polydispersity 1.1 – 1.9), this amplifies the influence of larger snow grains (low SSA/high optical diameter), increasing the exponential correlation length and the simulated microwave scattering.’*

485

490

495

## Answer to Reviewer 2:

500 This manuscript presents a comprehensive assessment of Arctic-modified SVS2-Crocus snow model performance across the forest-tundra ecotone and its implications for microwave remote sensing applications. Although the work addresses important questions regarding snow model transferability and microwave retrieval preparation, several methodological and interpretational concerns limit its impact.

Major comments:

505 The meteorological forcing data are from HRDPS, which is distributed in space with 25 km spatial resolution. You simulated snow cover based on a point scale, then you validated the simulated results using ground observations. I am confused about how the 2.5 km HRDPS data is applied to the model (point extraction vs. spatial interpolation) and whether simulations are run as single points or on a spatial grid. Did you downscale the  
510 forcing data before inputting them into the snow model? The spatial resolution of 25 km is too coarse, and it's hard to validate simulated snow cover from HRDPS using point-based ground observations, especially in the complex terrain. That's also one of the reasons for the uncertainties of simulation associated with wind speed within the HRDPS. Therefore, it could be more reasonable and decrease uncertainties to downscale the forcing data first  
515 if you did not do that.

The HRDPS has a spatial resolution of 2.5 km (Milbrandt et al., 2016). Meteorological forcing for our SVS2-Crocus simulations was directly extracted from the nearest HRDPS grid point corresponding to each site. Each site corresponds to a 1 km snow measurement  
520 transect sampled across specific vegetation types. Along each transect, multiple snow depth and SWE measurements were collected using a magnaprobe and SWE tube, and three snow pits were measured. These measurements capture the spatial variability of snow properties along each transect and therefore cannot be considered as single point-based ground observations. We acknowledge, however, that the spatial scale of these field sites does not match the 2.5 km resolution of the HRDPS grid.

525 Despite this mismatch, no downscaling was applied to the HRDPS forcing to locally adapt it to the sites of interest. The SVS2 configuration used in this study replicates what would be obtained from grid-point simulations using SVS2 on the same grid as the HRDPS. This setup reflects the current configuration of the National River and Surface Prediction System (NSRPS, Dunford et al., 2021) that provides analysis and forecast of land surface  
530 variables across Canada.

We acknowledge that the absence of meteorological downscaling introduces additional uncertainty when comparing simulated and observed snowpack properties. Two main sources of uncertainty related to the meteorological forcing exist in our study:

- 535
- I. Errors and systematic biases inherent to the short-term forecasts produced by the HRDPS; and
  - II. The absence of downscaling from the HRDPS grid resolution to the scale of the field sites.

This limitation will be explicitly mentioned in the discussion section of the revised manuscript:

540 *'The HRDPS forcing was used without downscaling to the local scale of the field sites. This introduces additional uncertainty in the simulations, arising from both inherent errors and biases from the HRDPS forecasts and from the mismatch between the 2.5 km HRPDS grid and the smaller-scale variability captured by our 1 km snow measurement transects.'*

545 It is not clear how the 120 ensemble members are statistically processed. When reporting metrics like "default RMSE and Arctic RMSE" (Lines 288-291), it is unclear whether these represent ensemble mean performance, median values, or some other aggregation method.

550 The RMSD (updated in response to Reviewer #1 comment) and SS scores are generated for the overall ensemble (difference and spread of the ensemble as whole). Calculating RMSD and SS for the ensemble allows us to evaluate the combined predictive performance and uncertainty of SVS2-Crocus, rather than focusing on individual ensemble members. To clarify the statistical processing in the manuscript, we will add the following sentence to the method section:

555 *'The RMSD and SS scores are generated for the overall ensemble, reflecting the difference and spread of the ensemble, allowing evaluation of the predictive performance and uncertainty of SVS2-Crocus.'*

The MS repeatedly claims that improved backscatter simulation will advance SWE retrieval capabilities, but this logic is confused. If SVS2-Crocus provides snow density and depth, SWE calculation is trivial and does not require backscatter simulation. The authors have not explained clearly why simulating backscatter (forward modeling) helps retrieve SWE from measured backscatter (inverse problem). The MS discovers substantial backscatter simulation errors (Lines 364-372) that would severely compromise any retrieval algorithm. The authors resort to ad hoc corrections (minimum SSA values, scaling factors) that lack physical justification and would not be transferable to operational scenarios and more study regions. In other words, the MS combines snow model evaluation with microwave retrieval algorithm development without clearly articulating which problem it aims to solve. If the goal is snow model improvement, the microwave component adds unnecessary complexity. If the final goal is advancing SWE retrieval, the methodology does not address the fundamental challenges of operational retrieval algorithms. Therefore, please clarify the study aims or objectives specifically.

575 We thank the reviewer for raising this important point. If SVS2-Crocus perfectly represented snow properties, there would be no need for backscatter experiments or satellite missions. However, because of known uncertainties in forcing and model structure, it is essential to quantify how these propagate through forward simulations of radar backscatter under configurations that are representative of operational use. While SWE can be directly calculated from snow depth and density simulated by SVS2-Crocus, our study does not aim to develop an operational SWE retrieval algorithm. Instead, our objective is to assess how uncertainties in snowpack model output affect forward-model backscatter simulations, with the longer-term goal of informing the development of SWE retrieval approaches that will rely on such models (e.g. Montpetit et al., 2025).

585 SVS2-Crocus simulates both bulk properties (e.g. SWE) and the vertical structure of snow layers over large domains, driven by distributed meteorological forcing from numerical weather prediction systems, surface analyses or reanalyses. Errors in simulated SWE arise from (i) uncertainties in the meteorological forcing (see response our response on

Line 24 of this manuscript), and (ii) structural limitations in the representation of snow and land surface processes. These errors can be reduced by assimilating SWE observations in SVS2-Crocus. However, in-situ SWE measurements are spatially sparse across the Arctic, which limits the effectiveness of data assimilation when relying solely on ground-based networks.

590

Current and future satellite missions aim to fill this gap by retrieving SWE from Ku-band backscatter over continental scales. Reliable SWE retrieval at Ku-band (e.g. Montpetit et al., 2025) requires a priori information on snow microstructure, which can be provided by SVS2-Crocus. Therefore, it is crucial to understand how accurately SVS2-Crocus represents snow microstructure and how uncertainties in these estimates propagate into simulated backscatter, since this will directly affect the performance of future SWE retrieval algorithms and data assimilation systems.

595

Our study evaluates backscatter simulated by SMRT resulting from three sets of driving data:

600

I. SMRT driven by detailed (~20-layer) SVS2-Crocus output forced by HRDPS meteorology (without downscaling), representing the best available simulated representation of the snowpack.

605

II. SMRT driven by SVS2-Crocus output forced by HRDPS meteorology (without downscaling) and simplified to three 'radar-equivalent' layers, representing a realistic operational setup for TSMM.

III. SMRT driven by snow pit observations, representing the best available measured representation of the snowpack. This configuration acts as the reference used to determine the quality of the SVS2-Crocus simulations.

610

By comparing these configurations, we quantify the impact of model structural uncertainty and snow microstructure representation on simulated backscatter. This approach provides an insight into how well model-driven simulations can reproduce observed radar responses across the forest-tundra ecotone and informs how SVS2-Crocus can best support future SWE retrieval and data assimilation systems.

The specific aims of the study are therefore as follows:

615

1. To evaluate the capacity of SVS2/Crocus driven by HRDPS meteorological forcing (without downscaling), to simulate snowpack properties (SWE, depth, bulk density, profiles of SSA and density) across the forest-tundra ecotone.

620

2. To evaluate the impact of an ensemble of simulated snow properties on Ku-band (13.5 GHz) backscatter using the Snow Microwave Radiative Transfer Model (SMRT; Picard et al., 2018), under three configurations:

a. SMRT driven by a detailed (~20-layer) SVS2-Crocus simulated snowpack.

b. SMRT driven by a simplified (3-layer) radar-equivalent SVS2-Crocus simulated snowpack, following the approach of Meloche et al., 2025.

625

c. SMRT driven by raw snow pit observations, representing the best available measured representation of the snowpack and serving as a reference for assessing model performance.

The last paragraph of the introduction will be modified as follows:

*'This study evaluates the impact of changing vegetation across the forest-tundra ecotone on simulated snowpack properties (e.g. SWE, depth, density, profiles of*

630 *density and SSA). Snow properties are simulated using the multi-physics ensemble*  
*version of Crocus (Lafaysse et al., 2017; Vionnet et al., 2012) embedded within the*  
*Soil, Vegetation and Snow version 2 land surface model (hereafter referred to as*  
635 *SVS2-Crocus; Vionnet et al., 2022; Woolley et al., 2024), driven by meteorological*  
*forcing data from the High Resolution Deterministic Prediction System without*  
*downscaling (HRDPS; Milbrandt et al., 2016). SVS2-Crocus simulations are compared*  
*to measurements at 7 sites across a 40-km transect of the Northwest Territories*  
*(NWT), Canada, that represent the transition from small shrubs to sparse evergreen*  
640 *needleleaf forest. The impact of an ensemble of simulated snow properties on Ku-*  
*band (13.5 GHz) backscatter using the Snow Microwave Radiative Transfer Model*  
*(SMRT; Picard et al., 2018), is then tested under three configurations:*

- d) *SMRT driven by a detailed (~20-layer) SVS2-Crocus simulated snowpack.*
- e) *SMRT driven by a simplified (3-layer) radar-equivalent SVS2-Crocus simulated*  
*snowpack, following the approach of Meloche et al., 2025.*
- f) *SMRT driven by raw snow pit observations, representing the best available*  
645 *measured representation of the snowpack and serving as a reference for*  
*assessing model performance.'*

We will also add this into the last paragraph of the discussion:

650 *'SVS2-Crocus simulates both bulk properties (e.g. SWE) and the vertical structure*  
*of snow layers over large domains, driven by distributed meteorological forcing*  
*from numerical weather prediction systems, surface analyses or reanalyses. Errors*  
*in simulated SWE arise from uncertainties in the meteorological forcing, and*  
*structural limitations in the representation of snow and land surface processes.*  
655 *These errors can be reduced by assimilating SWE observations in SVS2-Crocus.*  
*However, in-situ SWE measurements are spatially sparse across the Arctic, which*  
*limits the effectiveness of data assimilation when relying solely on ground-based*  
*networks. To address this limitation, current and future satellite missions aim to*  
*retrieve SWE from Ku-band backscatter over continental scales. Reliable SWE*  
*retrieval at Ku-band (e.g. Montpetit et al., 2025) requires a priori information on*  
660 *snow microstructure, which can be provided by SVS2-Crocus. Improvements to*  
*the simulation of snow SSA and Ku-band backscatter progress our capacity to*  
*retrieve SWE from satellites, which will be crucial for understanding the impact of*  
*climate change in seasonally snow-covered environments'*

Minor comments:

665 Lines 107-108, regarding the two forest sites, can you give a more detailed description of  
their location? They are under the canopy or canopy gaps?

At each field site, we measured snow pits at the start, middle, and end of a 1 km transect.  
At forested sites, one snow pit was measured in a canopy gap and two beneath the  
canopy, to capture the spatial variability in snow properties. This information will be added  
to Line 134 of the manuscript:

670 *'Snow pits were measured at the start, middle and end of a 1 km transect at each*  
*site to capture the spatial variability of snow properties, with forested sites sampled*  
*in a canopy gap and two locations beneath the canopy.'*

675 Lines 157-158, how and when (summer or winter) did you measure the polar vegetation heights? These heights (0.1-0.35 m) seem static, but shrub bending under snow load is dynamic. Did you consider that?

680 The polar vegetation heights (0.1-0.35 m) were measured in March; at the time each snow pit was sampled. These values represent the shrubs heights under the existing snow load, thereby accounting for the bending and compression of shrubs at the time of measurement. While shrub heights change dynamically under snow over time, since our evaluation of the snowpack model is conducted for the same date as measurements, it is appropriate to use these static heights in our simulations. At this stage, SVS2-Crocus does not consider the progressive bending of shrubs when snow accumulates during the winter. This limitation will be mentioned in the discussion in the revised manuscript as follows:

685 *'The polar vegetation heights used in our simulations (0.1 – 0.35 m) were measured under existing snow load and therefore account for the bending and compression of shrubs at the time of measurement (March). SVS2-Crocus does not currently consider the progressive bending of shrubs when snow accumulates during winter.'*

690 Lines 177-178, you mentioned the range of polar vegetation height (0.1-0.35 m) before. When you used polar vegetation height in Arctic SVS2-Crocus parameterization, did you use a fixed value or changing values? It's so simple to create a binary threshold at all sites (tundra, shrub, and forest): below this height = vegetation effects active, above = normal snow physics, especially several vegetation types in your study region. For example, why would 0.35 m shrub effects apply in 10 m tall forests?

695 The polar vegetation height in SVS2-Crocus represents the height of low vegetation (e.g. shrubs and sedges) that influence the properties of the basal snow layers by reducing snow compaction and limiting wind-packing. For each site, a fixed polar vegetation height was applied across all simulations. This value was selected as the most representative of the measurements collected within the snow pits along the 1 km transect at each site, capturing the spatial variability of shrubs and tundra vegetation. Both shrub and understory vegetation are present, and we aimed to represent these as realistically as possible. However, the use of a fixed value represents a current model limitation. The polar vegetation height does not represent tree height at the forested site. Separate values for tree height are specified in the SVS2-Crocus canopy scheme, which affects processes such as wind speed reduction within the forest canopy. The polar vegetation height instead corresponds to the low vegetation layer present beneath the trees. This distinction between tree height and polar vegetation height is clarified in Figure 1 and will be included within the text of the revised manuscript.

710 *'Polar vegetation height in SVS2-Crocus represents low vegetation (e.g. shrubs and sedges) that affect basal snow properties by reducing compaction and wind-packing. A fixed value, representative of shrub and understory vegetation measured in snow pits along each 1 km transect, was used for all simulations. However, this simplification represents a model limitation. At forested sites, polar vegetation height refers only to the understory layer, while tree height is separately defined in the canopy scheme.'*

715 Line 238, I know "TVC" represents Trail Valley Creek, but this is the first time you've used the abbreviation. You should also indicate its full name; similar problems also exist for

other sites. In addition, I'm confused about how you named the seven sites. Either all of them are named after places, or all of them are named after vegetation types.

720 We thank the reviewer for pointing out this inconsistency. This issue was also raised by Reviewer #1. For consistency and clarity, we have repeated our response to Reviewer #1 below, detailing the changes we will make. We will also change 'TVC' to 'Trail Valley Creek' and ensure that we indicate the full name of each site where it is first introduced.

We will refer to all sites by their individual names, as described in Figure 1. These are:

- 725
- Upper Plateau
  - Trail Valley Creek
  - Valley
  - Small Shrub
  - Mixed Shrub
- 730
- Shrub Tree
  - Havikpak

However, in section 4.2 (Profiles of density and SSA), we perform statistical analysis on groups of sites defined by their vegetation types, as outlined in Figure 1. This grouping is also clarified on Section 3.2.1 of the manuscript. The site groups are as follows:

- 735
- Tundra (Upper Plateau and Trail Valley Creek)
  - Deciduous Shrub (Valley, Small Shrub and Mixed Shrub)
  - Forest (Shrub Tree and Havikpak)

We acknowledge that this distinction may not have been sufficiently clear in the original text. To address this, we will modify the first paragraph of Section 4.2 to explicitly restate the grouping and refer the reader back to Figure 1. The revised paragraph will read as follows:

740

745 *'Figure 5 and 6 compare measured and simulated profiles of snow density and SSA for Upper Plateau, Small Shrub and Havikpak, representing three sites of contrasting vegetation type (see Fig. 1) for the 2021/22 and 2022/23 winter seasons, respectively. All remaining sites are displayed in Appendix B. We discuss the results from figures 5, 6, 7 and Appendix B with reference to the vegetation type, as classified in Fig. 1: Tundra (Upper Plateau, Trail Valley Creek), Deciduous Shrub (Valley, Small Shrub, Mixed Shrub) and Forest (Shrub Tree and Havikpak). Measured profiles of snow density at tundra and deciduous shrub sites exhibit the typical structure of an Arctic snowpack: low-density basal layers ranging between 150 kg m<sup>-3</sup> and 300 kg m<sup>-3</sup> overlain by higher density surface layers ranging between 300 kg m<sup>-3</sup> and 400 kg m<sup>-3</sup> (Fig. 5 & 6, Appendix B). At forest sites, measured snow density shows less variability throughout the snowpack with surface and basal layers exhibiting similar densities (Fig. 5 & 6, Appendix B: WS Mean: 196 kg m<sup>-3</sup> ; DHF Mean: 192 kg m<sup>-3</sup>). Despite differences in snow density, the pattern of measured SSA is consistent amongst all sites with lower SSA values for basal layers (ranging between 5 m<sup>2</sup> kg<sup>-1</sup> and 20 m<sup>2</sup> kg<sup>-1</sup> ) and higher SSA (ranging between 30 m<sup>2</sup> kg<sup>-1</sup> and 60 m<sup>2</sup> kg<sup>-1</sup>) values for near-surface layers (Fig. 5 & 6, Appendix B). The variability between measured pit profiles of density and SSA decreases from tundra to forest (Fig. 5 & 6, Appendix B).'*

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760

Figs. 5 and 6, It could be better to show different pit measurements in the legend.

765 We understand the reviewer's interest in distinguishing individual pit measurements in Figures 5 and 6. However, our focus is on capturing the overall variability across the site rather than the results from specific pits. The current figures allow us to adopt a spatially informed approach, reflecting the variability across the 1 km transect.

770 Lines 459-461, "some simulated profiles can be shallower than measured profiles as a function of the precipitation inputs meaning some polar vegetation heights encompass much of the simulated profile", is the snow thermal conductivity changes influenced by shrub considered during the parameterization processes? Except for the decreased wind-induced snow compaction, the changes in snow thermal conductivity are also important to snow energy and mass balance as well as soil thermal regime.

775 At the moment, SVS2-Crocus does not take into account several processes associated with the presence of shrubs: (i) the change of winter surface albedo in presence of erected shrubs above the snowpack (Belke Brea et al., 2020) (ii) the changes in solar radiation transmission within the snowpack (Domine et al., 2025) and (iii) the thermal bridging through shrubs branches that affect the thermal regime of the underlying soil (Domine et al., 2022). We will add a sentence into the manuscript as follows:

780 *'SVS2-Crocus does not currently account for several shrub-related processes such as changes in winter surface albedo due to erected shrubs (Belke Brea et al., 2020), alterations in solar radiation transmission within the snowpack (Domine et al., 2025), or thermal bridging through shrub branches affecting the underlying soil (Domine et al., 2022).'*

The Hedstrom and Pomeroy (1998) interception model requires some vegetation information, such as LAI and canopy coverage. Where did you get them?

785 Information about the canopy closure, CC, were derived from hemispherical pictures taken along the 1-km transect at both forest sites. The type of vegetation in SVS2 for these two sites was then specified as evergreen needleleaf trees. SVS2 uses a constant value for the LAI of individual trees composing a forest of evergreen needleleaf trees. This value is specified in a look-up table (see Table S2 in the Supplementary material of Vionnet et al (2025)) and we used the default value of 4 in our study. An effective LAI ( $LAI_{eff}$ ),  $LAI_{eff}$  (=  $CC * LA$ ) is then used to compute the maximum snow holding capacity used in the Hedstrom and Pomeroy (1998) interception model (Eq. 28 and 29 in Vionnet et al., 2025). A sentence to clarify this will be included in section 3.2.1 SVS2-Crocus of the manuscript:

795 *'Canopy cover density (CC) values ranged from 10 to 13% (Fig. 1), derived from hemispherical photographs taken along the 1-km transect at both forested sites (Essery et al., 2008). For these sites, the vegetation type in SVS2-Crocus was specified as evergreen needleleaf trees, for which the model uses a default leaf area index (LAI) of 4 (Vionnet et al., 2025, Table S2). An effective LAI,  $LAI_{eff}$  (=  $CC * LA$ ), was then used to compute the maximum snow holding capacity in the Hedstrom and Pomeroy (1998) interception model (Vionnet et al., 2025, Eq. 28-29).'*

800

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