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 both reviewers 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 2:

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:

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 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 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 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.

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 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:

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:

> *'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.'*

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.

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:

> *'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.

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).

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.

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.

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

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.
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.

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:

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.
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.

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 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 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 95 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 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:

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.'

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

'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. 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 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:

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:

> *'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'.*

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?

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:

> *'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.'*

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?

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.

> *'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.'

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.

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:

- Upper Plateau
- TVC
- Valley
- Small Shrub
- Mixed Shrub
- 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:

- 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:

'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^{-3} and 300 kg m^{-3} overlain by higher density surface layers ranging between 300 kg m^{-3} and 400 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 kg m^{-3} ; DHF Mean: 192 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 m^2 kg^{-1} and 20 m^2 kg^{-1}) and higher SSA (ranging between 30 m^2 kg^{-1} and 60 m^2 kg^{-}) 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).'

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

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.

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.

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:

'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?

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_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:

*'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).'

References

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