Author Response for "Multi-physics ensemble modelling of Arctic tundra snowpack properties", Woolley et al.

The authors would like to thank the editor and both reviewers for the time taken to read and review the original manuscript and for the great feedback provided which improves the manuscript. Our responses are in blue, modified text is in italics and reviewer comments are in black.

Reply to comments from Reviewer 1:

The font size on the figures (legends, axis labels, etc) throughout the paper should be increased to make them readable in print (including Figure 9).

Font size increased.

The author report that the vegetation effect does not allow for improved simulations compared to the standard crocus, and that this highlights the need to account for water vapor transport in snow. However, looking at the density profiles (fig 4 and 6), simulations do show a drop of density at the base. This drop seems of the same order as the ones reported in measurements, when observed. As you mentioned, the definition of what is the wind slab and what is the depth hoar could impact the conclusion of the statistical analysis. The simulated density drop indeed seems to impact less than the 40 to 70 % of the profile, as indicated as the range of DHF reported from the snow pits. An idea could be to compare bulk density of only the first 10 cm (or any other relevant value that for sure describe only depth hoar, even if not part of the depth hoar layer is not included). **Essentially, my question is to what extent the error in defining the depth hoar boundaries could have an impact on the conclusion regarding the proposed vegetation parameterizations. Some more comments could be done on that in the discussion.**

To investigate whether the DHF values selected for use within this study impact the statistical analysis for the *Basal Vegetation Effect* modifications, we followed the suggestion of the reviewer and evaluated the lowest 10 cm of each simulated and measured vertical profile. As measurements were not always available for the base of the snowpack due to the impact of shrubs and vegetation, we compared the lowest 10cm of each profile where measurements were available. We identified the depth in which the measured values began and removed any simulated values below this position in the vertical profile. We then extracted the lowest 10 cm of values from both the measured and simulated profiles and carried out a comparative statistical analysis. Statistical scores from the analysis are presented below:

Table 1: Mean, RMSE, SS and CRPS scores for measured and simulated snow density (kg m^{-3}) for the lowest 10 cm (starting where measurement profiles begin) for the March 2018, March 2019, March 2022 and March 2023 snow seasons.

		Mean	RMSE	SS	CRPS
Density (kg m^{-3})	Measured	234	-	-	-
	Default	277	69	0.6	51
	Arctic	262	79	1.1	35

We find that Arctic SVS2-Crocus simulates a mean depth hoar snow density that better matches measurements (by 15 kg m^{-3}) (Table 1). However, we find the simulation error is higher than default SVS2-Crocus (Table 1; default RMSE: 69 kg m^{-3}; Arctic RMSE: 79 kg m^{-3}). A better mean but higher RMSE indicates that while the average density from the Arctic SVS2-Crocus ensemble is closer to the average measured density, the ensemble has a higher variance than default SVS2-Crocus from the measurements. This is reflected in the higher SS score for Arctic SVS2-Crocus (Table 1; default SS: 0.6; Arctic: 1.1) and is due to the design of the *Basal Vegetation Effect* modifications.

We add the following to section 4.2 and Table 1 to the Appendix (Appendix C1):

As measurements were not always available for the base of the snowpack due to the impact of shrubs and vegetation, we compared the lowest 10 cm of each profile where measurements were available, for fair statistical analysis of the Basal Vegetation Effect modifications. Arctic SVS2-Crocus simulates a mean depth hoar snow density that better matches measurements (by 15 kg m^{-3}; Appendix C1) than default SVS2-Crocus, with a higher error (default RMSE: 69 kg m^{-3}; Arctic RMSE: 79 kg m^{-3}; Appendix C1) due to a larger ensemble spread leading to higher variance from the measurements.

We investigate Basal Vegetation Effect modifications R2V and R2D individually, and then combined as R21 (described in section 3.2.3). R2V and R21 produces a large ensemble spread, as they simulate basal densities that are more representative of measurements in comparison to R2D (Table 2). As we highlight in section 5.2 of the manuscript, we determine that the use of R21 due its high occurrence within the top 30 members from both the mixed and Arctic ensembles, can reduce basal layer densities that better match measured results, in comparison to default SVS2-Crocus. This is now further supported by the statistics presented within Table 2, where R21 produces a more representative mean value, lower RMSE and CRPS score out of all *Basal Vegetation Effect* modifications.

Table 2: Mean, RMSE, SS and CRPS scores for measured and simulated (specifically Basal Vegetation Effect modifications R21, R2D and R2V) snow density (kg m-3) for the lowest 10 cm (starting where measurement profiles begin) for the March 2018, March 2019, March 2022 and March 2023 snow seasons.

		Mean	**RMSE**	**SS**	**CRPS**
Density (kg m^{-3})	Measured	234	-	-	-
	R21	215	60	2.04	45
	R2D	300	74	0.50	55
	R2V	274	63	0.64	46

We add the following to section 4.2 and Table 2 to the appendix (Appendix C2):

Basal Vegetation Effect modifications are evaluated individually (as R2V and R2D) and then combined as R21 (described in section 3.2.3) producing a large ensemble spread. Analysis of the impact of each individual modification for the lowest 10 cm of the snowpack, highlight that modification R21 produces a mean value that is representative of measurements (measured mean: 234 kg m^{-3}; R21 mean; 215 kg m^{-3}; Appendix C2) with a lower RMSE (60 kg m^{-3}; Appendix C2) and CRPS (45 kg m^{-3}; Appendix C2) out of all Basal Vegetation Effect modifications. Modification R2D is not as effective in simulating basal layer densities (measured mean: 234 kg m^{-3}; R2D mean; 300 kg m^{-3}; RMSE; 74 kg m^{-3}; Appendix C2), impacting the overall statistical analysis of the Basal Vegetation Effect modifications.

We also modify a sentence within section 5.2:

Although statistically, the Basal Vegetation Effect modifications are unable to reduce basal layer densities that match those of observations (Table 2), the high relative occurrence of R21 within both the Arctic and mixed ensembles and the statistical analysis of the lowest 10 cm of the snow density profile, suggests the modification simulates snow densities that are more reflective of measured results, in comparison to default SVS2-Crocus parameterisations

We add the following information to section 3.0 Data and Methods for determining the selection of DHF boundaries as follows:

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., 2009), providing a sharper transition between wind slab and depth hoar that can be visibly identified. Where the transition between snow type occurs, the density and/or SSA value is noted and cross referenced with those presented in Fig.9 of Rutter et al. (2009).

Specific Comments:

Introduction

The second paragraph of the introduction (lines 49 – 67) focuses on the limitations of arctic snow modeling due to misrepresentation of some physical processes, not suited for the Arctic. This part provides a state of the art which is not fully convincing because some information are lacking and/or disorderly. For example, it is not mentioned what is the current issues regarding wind parameterization (is it too weak or too strong?), how is modeled the vegetation (is it accounted at all?) or why should we consider a different thermal conductivity. The process of water vapor transport is well described but is is actually not essential as it is not addressed in this paper (not modeled). Most of the missing information are provided latter in the paper but should be described already in the state of the art so that the reader understands the motivation for the work done. This is why I suggest that, for each of the processes addressed in this paper, which are the effect of wind, the effect of vegetation, and the snow thermal conductivity, you check that the following information are provided in a well-structured way:

- description of the physical processes and the consequences on snow and what is different in the arctic

- how it is modeled or not in "standard" snow model (crocus, snowpack) and what are the errors done by applying it to the arctic (quantify if possible)

- if any, what are the modifications for the arctic already presented and how do they improve the situation, what is left to be addressed (contributions of this paper).

We modify the second paragraph to include the relevant and requested information:

Detailed multi-layered snowpack models primarily developed for avalanche forecasting, Crocus (Vionnet et al., 2012) and SNOWPACK (Bartelt and Lehning, 2002),do not perform well when applied within Arctic environments (Domine et al., 2019; Fourteau et al., 2021; Barrere et al., 2017). Despite showing reasonable agreement in their simulation of snow depth and SWE of Arctic snowpacks (Barrere et al., 2017; Gouttevin et al., 2018; Krinner et al., 2018; Domine et al., 2019; Royer et al., 2021; Krampe et al., 2021; Lackner et al., 2022) both models simulate profiles of increasing density with snow depth because both Crocus and SNOWPACK were originally developed to simulate alpine snow. Further uncertainties arise in the simulation of snow density due to an underestimation in wind-induced compaction (Barrere et al., 2017; Royer et al., 2021; Lackner et al., 2022), misrepresentation of the impact of basal vegetation on compaction and metamorphism (Gouttevin et al., 2018; Royer et al., 2021), thermal conductivity formulations (Royer et al., 2021; Dutch et al., 2022) and omission of water vapour flux transport (Brondex et al., 2023) within both models.

In the Arctic, high wind speeds compact the snowpack surface, creating high-density wind slab snow layers (King et al., 2020; Derksen et al., 2014). The effect of wind on surface snow density has been found to be underestimated in Crocus, leading to underestimations in simulated surface snow density (Barrere et al., 2017). Attempts to account for an underestimation in wind speed have been proposed by Barrere et al. (2017) and Royer et al. (2021) where wind speed during snow precipitation events and the rate of snow compaction were increased. Based upon analysis of field measurements, Barrere et al. (2017) and Royer et al. (2021) also increased the maximum density constraint from 350 kg m^{-3} to 600 kg m^{-3} for Arctic applications.

Basal vegetation (shrubs and sedges) modifies temperature gradients within the snowpack by reducing compaction and enhancing snow metamorphism, which promotes depth hoar formation (Domine et al., 2016; Domine et al., 2022). The ability of basal vegetation to promote the development of depth hoar is currently not considered within Crocus or SNOWPACK where compaction due to the weight of the overlying snow is the dominant process in shaping density profiles (Vionnet et al., 2012; Bartelt and Lehning, 2002). To consider the presence of basal vegetation, Gouttevin et al. (2018) and Royer et al. (2021) proposed to deactivate wind compaction and increase snow viscosity below a set vegetation height which contributed towards density reduction and enhanced grain growth in basal layers.

Thermal conductivity of snow is often computed as a function of density within many snowpack models (Gouttevin et al., 2018), with a number of different relationships proposed (Yen, 1981; Calonne et al., 2011; Sturm et al., 1997). The parameterisation of Sturm et al. (1997) has been found to produce better results for Arctic snow than the default Crocus parameterisation of Yen (1981), due to its development on Arctic and sub-Arctic snow and has recently been implemented into Crocus (Royer et al., 2021; Calonne et al., 2011). Thermal conductivity formulations of Calonne et al. (2011), who use 3D tomographic images of most snow types, and Fourteau et al. (2021), who propose a formulation suitable for temperatures within Arctic snowpacks have also been found to improve the simulation of snow thermal conductivity at an Arctic site (Dutch et al., 2022). Calonne et al. (2011) is available for use within the ensemble system version of Crocus (Ensemble System Crocus; ES-CROC; Lafaysse et al., 2017) however the parameterisation of Fourteau et al. (2021) is yet to be implemented within Crocus.

Strong temperature gradients within an Arctic snowpack generate vertical water vapour fluxes that redistribute mass from the bottom to the top of the snowpack, leading to the formation of low-density basal depth hoar layers (Bouvet et al., 2023; Weise, 2017). Attempts have been made to implement water vapour diffusion into Crocus (Touzeau et al., 2018), SNOWPACK (Jafari et al., 2020) and SNTHERM (Jordan, 1991). However, no approach was successful in accounting for all aspects of vapour diffusion or able to be numerically stable at the typical time steps of snowpack models and is therefore currently not simulated (Brondex et al., 2023).

The third paragraph of the introduction (line 69 -83) focuses on another issue on arctic snow modeling, which, this time, concerns the model evaluation method. If this is correct, I suggest to change the first sentence of this paragraph so that this new topic is introduced. The sentence in the current version of the paper refers to issues related to physical processes, so to the topic of to the previous paragraph. It could start as “Another limitation in Arctic snow modeling concerns the method for model evaluation. Indeed, previous evaluation of simulated arctic snow density (e.g. Gouttevin …) neglect uncertainties that arise from ...”

We now start the paragraph with the following sentence taken from later in the original paragraph to introduce the new topic:

An ensemble modelling approach allows evaluation of uncertainties in all the main snowpack process representations, both individually as well as in combination with each other, to better *quantify overall modelling error (Lafaysse et al., 2017; Essery et al., 2013). Previous attempts to simulate Arctic snow density profiles focus on individual modifications to existing snow physical processes that account for high wind speeds, the presence of basal vegetation, and/or better simulations of snow thermal conductivity (Barrere et al., 2017; Lackner et al., 2022; Royer et al., 2021; Gouttevin et al., 2018).*

Line 56: "strong temperature gradients generate water vapour flux transport that redistributes mass from the bottom to the top of the snowpack, leading to the formation of low-density basal depth hoar layers (Domine et al., 2016b; Fourteau et al., 2021)". Citations here should refer to observation, Fourteau et al 2021 did modeling, if my not mistaking. Citation of the experimental work of Weise's thesis (in Chap.5) and Bouvet et al. 2023 could be included.

References changed to include experimental work of Bouvet et al. (2023) and Weise (2017):

strong temperature gradients generate water vapour flux transport that redistributes mass from the bottom to the top of the snowpack, leading to the formation of low-density basal depth hoar layers (Bouvet et al., 2023; Weise, 2017).

Line 65: Is "Domine et al 2016b and Domine et al. 2019" the reference papers to describe wind effect on arctic snow? Papers that describe this process should be given here (maybe the references provdided line 210).

References changed to include the work of King et al. (2020) and Derksen et al. (2014):

Furthermore, high Arctic wind speeds compact the surface of the snowpack leading to the development of high-density wind slab snow layers (King et al., 2020; Derksen et al., 2014).

Line 65 "Attempts to account for missing processes that specifically impact Arctic snowpack properties have been made by implementing simplified adaptations to existing snow physical processes (Gouttevin et al., 2018; Royer et al., 2021; Barrere et al., 2017; Lackner et al., 2022)." This sentence should be more explicit or deleted here.

We have deleted this sentence but modified the second sentence of the third paragraph (Line 66) to provide the reader with the same information. This is shown in detail in our response to the first specific comment on line 34 of this document:

Previous attempts to simulate Arctic snow density profiles focus on individual modifications to existing snow physical processes that account for high wind speeds, the presence of basal vegetation, and/or better simulations of snow thermal conductivity (Barrere et al., 2017; Lackner et al., 2022; Royer et al., 2021; Gouttevin et al., 2018).

Line 87: It should be mentioned in this paragraph if the parameterizations implemented in crocus are new or from the literature.

Sentence on line 87 modified to state that the parameterizations implemented are from literature:

This study uses the multi-physics ensemble version of Crocus (Lafaysse et al., 2017; Vionnet et al., 2012) embedded within the Soil, Vegetation and Snow version 2 (SVS2) land surface model (hereby referred to as SVS2-Crocus, Garnaud et al., 2019; Vionnet et al., 2022) to evaluate the impact on simulated Arctic snowpack properties by modifying parametrisations of falling snow density, snowdrift, compaction and thermal conductivity that have been proposed within previous literature..

Line 103: how is the topography of the study site?

The following sentence is added, to describe the topography at Trail Valley Creek:

The terrain consists of mineral earth hummocks that range in diameter between 0.4 to 1.0 m and inter-hummock areas of peat (Quinton and Marsh, 1999).

Line 223: “Following the approach of Gouttevin et al. (2018), Royer et al. (2021) and Domine et al. (2016a) deactivated wind compaction and increased η under a set vegetation height.” → What was the improvement of this modification.

The following sentence was modified, to outline the improvement of the modification:

Following the approach of Domine et al. (2016), Gouttevin et al. (2018) and Royer et al. (2021) deactivated wind compaction and increased η under a set vegetation height which reduced the rate of densification through compaction processes.

Line 225: “Both options” → It is not clear which options are meant here.

Changed to:

Modifications R2D and R2V are also investigated together in combination as R21.

Line 259: “… and are applied to the normalized profiles of simulated density and SSA” → describe what are the normalized profiles.

The following sentence is added, to explain the normalized profiles:

Measured and simulated density and SSA profiles report different vertical resolutions; therefore, we rescale each individual profile to a 0.005 m grid interpolated using layer thickness, beginning at 0 m and ending at 1 m.

Line 260: “Vegetation in the base of an Arctic snowpack makes density and IceCube measurements difficult meaning measurements do not always reach the base of the snowpack for evaluation of simulated basal layer density and SSA.” → to be reformulated “which might impact the evaluation of simulated basal layer density and SSA.”

Reworded to:

Vegetation in the base of an Arctic snowpack makes density and IceCube measurements difficult meaning measurements do not always reach the base of the snowpack which may impact the evaluation of simulated basal layer density and SSA.

Line 270: The start of the paragraph should introduce what do we look at now, instead of going directly into details. I would suggest something like “Over the years 1991-2023, different result can be found in the evolution of snow depth and SWE over the course of the winter between the model and the measurements. Over estimation, good agreement and under estimation can be observed depending on the year considered, as illustrated in Figure 2. These biases can be explained … ect”.

A new sentence has been added to introduce the paragraph:

Differences in the seasonal evolution of simulated and measured snow depth, SWE and bulk density can be found over the 1991-2023 period. Model over-estimation, good model agreement and model under-estimation in simulated snow depth and SWE are observed when compared to measurements, depending on the year considered (Fig. 2).

Line 277: “In this case, a snow drift in the SR50 footprint can lead to exaggerated differences between simulated and measured snow depth.” → Is this feature was observed during the field campaign or is it an hypothesis?

We added the following sentence to state that the snow drift was an observed feature:

In this case, a snow drift observed in the SR50 footprint during field campaigns, caused by surrounding topography and prevailing wind direction, led to exaggerated differences between simulated and measured snow depth.

Line 287: Here the data that we look at now should be introduced first, otherwise it is unclear. Such as "We look now at the statistical scores when comparing model and measurements over the entire 1991-2023 period at the time of the snow course measurement, i.e. around the peak SWE accumulation."

We modify the start of the sentence to introduce the data:

Statistical analysis of simulated and observed peak SWE for 1991-2003 demonstrate that both default and Arctic SVS2-Crocus show good agreement with measured results for the simulation of SWE (default RMSE: 55 kg m-2; Arctic RMSE: 55 kg m-2) and snow depth (default RMSE: 0.20 m; Arctic RMSE: 0.17 m) at TVC (Fig. 3, Table 1).

Line 289: "Deeper snow depths are simulated by default SVS2-Crocus (default mean: 0.54 m; Arctic mean: 0.47 m) due to the Wind Effect modifications applied to Arctic SVS2-Crocus resulting in increased density in the surface layers of the snowpack, leading to higher bulk density (default mean: 239 kg m-3; Arctic mean: 278 kg m-3; Table 1, Appendix B3) and shallower snow depths." → This sentence should be reformulated.

Sentence reformulated to:

Wind Effect modifications applied to Arctic SVS2-Crocus increase surface layer density leading to a higher bulk density (default mean: 239 kg m^{-3}; Arctic mean: 278 kg m^{-3}; Table 1, Appendix B3) and shallower snow depths (default mean: 0.54 m; Arctic mean: 0.47 m) than default SVS2-Crocus.

The first paragraph is made of an overview of the snowpack structure at TVC. Then details on the dataset are provided and seem out of context. They seem to come to early in the result, before an overview or a general description of the dataset is provided (following paragraphs), which make it difficult to follow. I would suggest to move them lower down in the paper.

We revise the leading sentences to introduce the dataset discussed within each paragraph:

Line 344: *We first analyse measured profiles of density at TVC across the 2018/19 winter and the four winter seasons for a March snowpack.*

Line 385: *Over the course of the 2018/19 winter season, default SVS2-Crocus simulated a snowpack subject to consistent compaction, with basal layers increasing in density from ~200 kg m^{-3} in November 2018 to ~300 kg m^{-3} in March 2019 (Fig. 4).*

Line 395: Across the four winter seasons for a March snowpack, the dominance of compaction is clear when using default SVS2-Crocus where the ensemble simulated high-density basal layers (default mean DHF: 268 kg m^{-3}) overlain with lower density surface layers (default mean WS: 177 kg m^{-3}) (Table 2, Fig. 6) across each year.

Line 232: "November 2018 shows less variability and range in snow density than other snow seasons (Fig. 4) as the snowpack was shallow and metamorphism in basal layers and compaction in surface layers had little time to affect the density." → unclear. Do you compare snow in November with snow in later months? in early season, snow had less time to evolve? Or does the comment refer to the year 2018 which was special? Again, this specific comment is hard to follow, as the reader is not yet familiar with the data / figures, which are actually described lower down.

We agree this sentence may lead to some confusion. We compare the structure of the density profile with other snow seasons to help describe how this evolves. Along with the restructure outlined in our response to the previous comment, we have added a new sentence to paragraph 2 of section 4.2 to give the reader a description of the data about to be discussed:

We first analyse the measured profiles of density at TVC across the 2018/19 winter and the four winter seasons for a March snowpack.

We then elaborate on our description and comparison of the November 2018 profile with other snow seasons as follows:

The density profile from November 2018 was measured early in the snow season and shows less variability and range than other snow seasons (Fig. 4) as the snowpack was shallow and metamorphism in basal layers and compaction in surface layers had little time to affect the density.

Line 235: "Heightened variability in the density of the top 20% of the January 2019, March 2019 and March 2022 snowpacks was more pronounced than in other winter seasons due to the timing of sampling relative to a fresh snowfall event". → unclear. Do you mean that the variability observed in snow density at the top 20% at these dates could have been introduced by a changing snowpack during the measurements, as they were performed during a snow fall.

We modify this sentence for clarity:

Variability in the density of the top 20% of the January 2019, March 2019 and March 2022 snowpacks was greater than in other winter seasons due to sampling during a fresh snowfall event (Fig. 4 & 6).

In the paragraph line 357 – 365, the rather sharp drop of density reported in the simulated profiles with the arctic version of crocus needs to be described in the text, as it seems an important feature of the modeling. It differs strongly with the standard crocus. The fact that this sharp drop comes from the modified parameterizations of the vegetation effect (if I'm not mistaken) could also be pointed out.

We have modified the paragraph to include the following sentence:

As the season progresses, and snow depth increases, the Basal Vegetation Effect modifications counteract the dominance of compaction found within default SVS2-Crocus and lead to a sharp drop in simulated density (reduction of ~ 50 kg m^{-3} in November 2018). This decrease in density is retained within the snowpack over the entire winter season, with a greater reduction of ~ 150 kg m^{-3} simulated by March 2019.

Line 373: "density" → mean density

Changed.

Line 398: "The Arctic SVS2-Crocus ensemble was however more skilled at capturing the variability in measurements" → It is not clear to me if this comment is relevant. In which way the arctic crocus would be more tuned / suited to capture spatial variability. Which introduced parameterizations would allow for that. If so, it should be described here.

We agree that this comment is not relevant and will remove from the manuscript.

Line 427 : “As these modifications were developed to consider Arctic processes, it is likely that they are better at simulating physical processes that occur in the Arctic environment over the default parameterisations, leading to lower CRPS scores.” → to be deleted, it was shown and quantified in the sentence above.

Sentence deleted.

Line 446: “Snowdrift parameterisations implemented into Arctic SVS2-Crocus modify the microstructure of snow grains during blowing snow events, which occur frequently at TVC.” → should this sentence be in the discussion?

We agree that this sentence should be within the discussion and have moved it to within paragraph 4 of section 5.2 as follows:

Arctic modifications R21F, R21W and R21R are dominant parameterisations within the snowdrift scheme that lead to lower CRPS scores for the simulation of SSA as they work to modify the microstructure of snow grains during blowing snow events, which occur frequently at TVC.

Line 504: “For the same reason, basal densities using default SVS2-Crocus may be underestimated.” → please provide more explanation of this link.

Through this sentence we intended to state that the statistical scores using default SVS2-Crocus are underestimated, due to the lack of measurements in the base of the snowpack. As default SVS2-Crocus is subject to densification, leading to higher basal densities, the statistical scores for the DHF would in fact be higher than what is shown within this study. We have elaborated on the above sentence to provide more detail on why the basal densities using default SVS2-Crocus may be underestimated:

For this same reason, statistical scores for default SVS2-Crocus may be underestimated for simulation of basal layer densities.

Line 520 : “The Basal vegetation effect is …” → “In this case the Basal vegetation effect is …”

Sentence changed to:

In this case, the Basal Vegetation Effect is activated immediately, causing compaction to occur at a very low rate where low basal densities are then retained within the snowpack throughout the entire winter.

Conclusion:

I would suggest to include a comment on the potential to improve arctic model evaluation by using dataset that allow to better capture snow properties at and near the base, especially to evaluate the parameterizations of the vegetation effect. Your study pointed out the challenge (but the need) of having density and SSA data near the ground due to the measurement method used.

We add the following sentence to the first paragraph of the conclusion outlining how an improved dataset would allow better evaluation of the parameterisations of the vegetation effect:

The ability to evaluate the simulation of microstructure properties at the base of the snowpack and the performance of the Basal Vegetation Effect parameterisations would benefit from the use of the snow micro penetrometer (SMP) (Johnson and Schneebeli, 1999), that is not hindered by the presence of basal vegetation and can reach the base of the snowpack.

Reply to comments from Reviewer 2:

In the introduction, you mention the problems of site specific calibration of parameter choices, which you avoid here by working with a set of parameters calibrated for different sites. But that doesn't prevent your conclusions from being site specific. This is more of a suggestion than a comment, but other observations are available at other Arctic sites, for instance in Vargel et al. (2020), which would make it easy to elaborate on this point.

We understand our conclusions are currently specific to the site of Trail Valley Creek. The goal of this paper was to explore the effect and interaction of Arctic parameterisations and identify preferential combinations of parameters which we can now test elsewhere. Our current work aims to evaluate the performance of our parameter choices at different sites across the tundra-taiga ecotone, where we will also look into the work of Vargel et al., 2020 to support this.

L109: How is the data filtered? Is the method known?

We add the following sentence to include information about how the data is filtered:

Depths below 0 m and above instrument sensor height (1.63 m) and abrupt jumps or spikes (negative or positive) that lie outside the reasonable range of values within the SR50A snow depth data were removed.

L137: What is this most suitable option based on?

The temperature threshold was selected based upon qualitative assessment of the impact of temperature on precipitation partitioning at TVC (between 0 ^{o}C and 5 ^{o}C) compared with observations of the precipitation type from the TVC Main Meteorological Station (TMM) and the adjacent Meteorological Service of Canada (MSC) weather station.

We add the following sentence to section 3.2.1 to describe this:

A sensitivity analysis into the correct temperature threshold by which to partition precipitation was carried out (testing values between 0 ^{o}C and 5 ^{o}C) by comparing observations of the precipitation type from TMM and the immediately adjacent (~ 5 m) Meteorological Service of Canada (MSC) weather station, finding 1 ^{o}C as the most suitable option for TVC.

Figs. 4,5,6,7,8: Increase label size and legend and explain what is normalized depth in the text for better readability. Wouldn't it be more practical to display the observations and the model on the same graph.

Font size increased.

We add a description of the normalized depth, this is outlined in our response to Reviewer 1 (Line 210 of this document).

Including both the model output and observations on the same graph made visual analysis of the shape and differences in profiles difficult. We decided to separate model output and observations to allow ease in the analysis by readers.

Reply to comments from the editor:

Line 84: Low-density snow is commonly snow with a density < 150 kg/m3. I suggest you define what you mean by low-density snow, and low-density depth hoar layers.

We thank the editor for outlining our use of 'low-density snow' and 'low-density depth hoar' interchangeably and understand how this could lead to confusion. We have modified the manuscript by separating the two phrases (outlined in the examples below and modified throughout the manuscript):

Line 66: *Basal vegetation (shrubs and sedges) modifies temperature gradients within the snowpack by reducing compaction and enhancing snow metamorphism, which promotes the formation of depth hoar (Domine et al., 2016; Domine et al., 2022).*

Line 348: *Measured profiles of density exhibit the typical structure of Arctic snowpacks: low-density basal layers …*

We have also modified our use of 'high-density snow' and 'high-density wind slab' throughout the manuscript for clarity.

Line 133: hard hardness (not finger hardness).

Changed.

Line 355 (and elsewhere): The preferred date format in TC is 15 January 2018 (instead of 15^{th} January 2018). In addition, with reference to line 58 and to avoid any misconception, it is not the case in Alpine snow covers that density always increases with increasing snow depth (please see the example attached). Also, models can handle this, although not always perfectly.

Dates have been changed to the preferred format.

Thank you for outlining this misconception and for providing the example. We have changed the sentence on Line 53 to avoid this:

Despite showing reasonable agreement in their simulation of snow depth and SWE of Arctic snowpacks (Barrere et al., 2017; Gouttevin et al., 2018; Krinner et al., 2018; Domine et al., 2019; Royer et al., 2021; Krampe et al., 2021; Lackner et al., 2022) both models ***often*** *simulate profiles of increasing density with snow depth because both Crocus and SNOWPACK were originally developed to simulate alpine snow.*

References

Barrere, M., Domine, F., Decharme, B., Morin, S., Vionnet, V., and Lafaysse, M.: Evaluating the performance of coupled snow–soil models in SURFEXv8 to simulate the permafrost thermal regime at a high Arctic site, Geoscientific Model Development, 10, 3461-3479, 10.5194/gmd-10-3461-2017, 2017.

Bartelt, P. and Lehning, M.: A physical SNOWPACK mdoel for the Swiss avalanche warning Part I: numerical model, Cold Regions Science and Technology, 35, 123-145, 2002.

Bouvet, L., Calonne, N., Flin, F., and Geindreau, C.: Heterogeneous grain growth and vertical mass transfer within a snow layer under a temperature gradient, The Cryosphere, 17, 3553-3573, 10.5194/tc-17-3553-2023, 2023.

Brondex, J., Fourteau, K., Dumont, M., Hagenmuller, P., Calonne, N., Tuzet, F., and Löwe, H.: A finite-element framework to explore the numerical solution of the coupled problem of heat conduction, water vapor diffusion and settlement in dry snow (IvoriFEM v.0.1.0), Geoscientific Model Development, 10.5194/gmd-2023-97, 2023.

Calonne, N., Flin, F., Morin, S., Lesaffre, B., du Roscoat, S. R., and Geindreau, C.: Numerical and experimental investigations of the effective thermal conductivity of snow, Geophysical Research Letters, 38, n/a-n/a, 10.1029/2011gl049234, 2011.

Derksen, C., Lemmetyinen, J., Toose, P., Silis, A., Pulliainen, J., and Sturm, M.: Physical properties of Arctic versus subarctic snow: Implications for high latitude passive microwave snow water equivalent retrievals, Journal of Geophysical Research: Atmospheres, 119, 7254-7270, 10.1002/2013jd021264, 2014.

Domine, F., Barrere, M., and Morin, S.: The growth of shrubs on high Arctic tundra at Bylot Island: impact on snow physical properties and permafrost thermal regime Biogeosciences Discussions, 10.5194/bg-2016-3, 2016.

Domine, F., Fourteau, K., Picard, G., Lackner, G., Sarrazin, D., and Poirier, M.: Permafrost cooled in winter by thermal bridging through snow-covered shrub branches, Nat Geosci, 15, 554-560, 10.1038/s41561-022-00979-2, 2022.

Domine, F., Picard, G., Morin, S., Barrere, M., Madore, J.-B., and Langlois, A.: Major Issues in Simulating Some Arctic Snowpack Properties Using Current Detailed Snow Physics Models: Consequences for the Thermal Regime and Water Budget of Permafrost, Journal of Advances in Modeling Earth Systems, 11, 34-44, 10.1029/2018ms001445, 2019.

Dutch, V. R., Rutter, N., Wake, L., Sandells, M., Derksen, C., Walker, B., Hould Gosselin, G., Sonnentag, O., Essery, R., Kelly, R., Marsh, P., King, J., and Boike, J.: Impact of measured and simulated tundra snowpack properties on heat transfer, The Cryosphere, 16, 4201-4222, 10.5194/tc-16-4201-2022, 2022.

Fourteau, K., Domine, F., and Hagenmuller, P.: Impact of water vapor diffusion and latent heat on the effective thermal conductivity of snow, The Cryosphere, 15, 2739-2755, 10.5194/tc-15-2739-2021, 2021.

Garnaud, C., Bélair, S., Carrera, M. L., Derksen, C., Bilodeau, B., Abrahamowicz, M., Gauthier, N., and Vionnet, V.: Quantifying Snow Mass Mission Concept Trade-Offs Using an Observing System Simulation Experiment, Journal of Hydrometeorology, 20, 155-173, 10.1175/jhm-d-17-0241.1, 2019.

Gouttevin, I., Langer, M., Löwe, H., Boike, J., Proksch, M., and Schneebeli, M.: Observation and modelling of snow at a polygonal tundra permafrost site: spatial variability and thermal implications, The Cryosphere, 12, 3693-3717, 10.5194/tc-12-3693-2018, 2018.

Jafari, M., Gouttevin, I., Couttet, M., Wever, N., Michel, A., Sharma, V., Rossmann, L., Maass, N., Nicolaus, M., and Lehning, M.: The Impact of Diffusive Water Vapor Transport on Snow Profiles in Deep and Shallow Snow Covers and on Sea Ice, Frontiers in Earth Science, 8, 10.3389/feart.2020.00249, 2020.

Johnson, J. B. and Schneebeli, M.: Characterizing the microstructural and micromechanical properties of snow, Cold Regions Science and Technology, 30, 1999.

Jordan, R.: A One-Dimensional Temperature Model for a Snow Cover - Technical Documentation for SNTHERM.89, Cold Regions Research and Engineering Laboratory, 1991.

King, J., Howell, S., Brady, M., Toose, P., Derksen, C., Haas, C., and Beckers, J.: Local-scale variability of snow density on Arctic sea ice, The Cryosphere, 14, 4323-4339, 10.5194/tc-2019-305, 2020.

Krampe, D., Kauker, F., Dumont, M., and Herber, A.: On the performance of the snow model Crocus driven by in situ and reanalysis data at Villum Research Station in northeast Greenland, The Cryosphere, 10.5194/tc-2021-100, 2021.

Krinner, G., Derksen, C., Essery, R., Flanner, M., Hagemann, S., Clark, M., Hall, A., Rott, H., Brutel-Vuilmet, C., Kim, H., Ménard, C. B., Mudryk, L., Thackeray, C., Wang, L., Arduini, G., Balsamo, G., Bartlett, P., Boike, J., Boone, A., Chéruy, F., Colin, J., Cuntz, M., Dai, Y., Decharme, B., Derry, J., Ducharne, A., Dutra, E., Fang, X., Fierz, C., Ghattas, J., Gusev, Y., Haverd, V., Kontu, A., Lafaysse, M., Law, R., Lawrence, D., Li, W., Marke, T., Marks, D., Ménégoz, M., Nasonova, O., Nitta, T., Niwano, M., Pomeroy, J., Raleigh, M. S., Schaedler, G., Semenov, V., Smirnova, T. G., Stacke, T., Strasser, U., Svenson, S., Turkov, D., Wang, T., Wever, N., Yuan, H., Zhou, W., and Zhu, D.: ESM-SnowMIP: assessing snow models and quantifying snow-related climate feedbacks, Geoscientific Model Development, 11, 5027-5049, 10.5194/gmd-11-5027-2018, 2018.

Lackner, G., Domine, F., Nadeau, D. F., Lafaysse, M., and Dumont, M.: Snow properties at the forest-tundra ecotone: predominance of water vapour fluxes even in thick moderately cold snowpacks, The Cryosphere, 16, 3357-3373, 10.5194/tc-2022-19, 2022.

Lafaysse, M., Cluzet, B., Dumont, M., Lejeune, Y., Vionnet, V., and Morin, S.: A multiphysical ensemble system of numerical snow modelling, The Cryosphere, 11, 1173-1198, 10.5194/tc-11-1173-2017, 2017.

Quinton, W. L. and Marsh, P.: A conceptual framework for runoff generation in a permafrost environment, Hydrological Processes, 13, 2563-2581, 10.1002/(sici)1099-1085(199911)13:16<2563::Aid-hyp942>3.0.Co;2-d, 1999.

Royer, A., Picard, G., Vargel, C., Langlois, A., Gouttevin, I., and Dumont, M.: Improved Simulation of Arctic Circumpolar Land Area Snow Properties and Soil Temperatures, Frontiers in Earth Science, 9, 10.3389/feart.2021.685140, 2021.

Rutter, N., Essery, R., Pomeroy, J., Altimir, N., and Andreadis, K.: Evaluation of forest snow processes models (SnowMIP2), Journal of Geophysical Research, 114, 10.1029/2008JD011063, 2009.

Sturm, M., Holmgren, J., König, M., and Morris, K.: The thermal conductivity of seasonal snow, Journal of Glaciology, 43, 26-41, 10.3189/s0022143000002781, 1997.

Touzeau, A., Landais, A., Morin, S., Arnaud, L., and Picard, G.: Numerical experiments on vapor diffusion in polar snow and firn and its impact on isotopes using the multi-layer energy balance model Crocus in SURFEX v8.0, Geoscientific Model Development, 11, 2393-2418, 10.5194/gmd-11-2393-2018, 2018.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J. M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geoscientific Model Development, 5, 773-791, 10.5194/gmd-5-773-2012, 2012.

Vionnet, V., Verville, M., Fortin, V., Brugman, M., Abrahamowicz, M., Lemay, F., Thériault, J. M., Lafaysse, M., and Milbrandt, J. A.: Snow Level From Post-Processing of Atmospheric Model Improves Snowfall Estimate and Snowpack Prediction in Mountains, Water Resources Research, 58, 10.1029/2021wr031778, 2022.

Weise, M.: Time-lapse tomography of mass fluxes and microstructural changes in snow, 2017.
Yen, Y.-C.: Review of the thermal properties of snow, ice and sea ice, Tech. Rep. , Cold Regions Research and Engineering Laboratory, Havover, NH. 1981.