HESS-2023-191 - How does a warm and low-snow winter impact the snow cover dynamics in a humid and discontinuous boreal forest? An observational study in eastern Canada

Responses to the Anonymous Referee #2

We would like to thank the anonymous referee #2 for providing relevant comments and suggestions. Based on these, we propose some changes to the original manuscript and its supplementary material. We hope that these changes, if they are accepted, will better place our study in the context of past and future climate and emphasize the originality of our work. Our answers below are in blue, whereas excerpts from the manuscript are in *italic* with modifications in ***bold.***

This manuscript provides a data-rich description of two winters at Montmorency Forest (Québec, Canada) with contrasting meteorological conditions. The manuscript is interesting, easy to read and data are presented in thorough and clear manner. However, I have a number of comments that the authors may wish to consider to help guide the clarity and purpose of the messages in this paper, for the wider community.

Major comments

1. The authors do a good job to realize their first objective – to quantify and compare the effect of snow under forest canopy and in canopy gaps on soil properties around the phase boundary and snow properties. This creates a thorough descriptive narrative, but which very largely reinforces what we already know, and struggles to justifiably generalize beyond the study site.

   a) Snow is well known to have a very important influence on insulating the relatively cold winter air temperatures from warmer soil. Very broadly, shallow snow means cooler soils and vice versa. Slater et al. 2017 (doi:10.5194/tc-11-989-2017) demonstrated that at effective mean snow depths of 50 cm the influence of the atmosphere on soil temperatures decouples. Hence shallow sub-canopy snow at Montmorency (< 50 cm) has a bigger influence on the variability of soil temperatures relative to deeper snow in gaps.

Thank you for the comment and the reference from Slater et al., (2017). Indeed, it is well known that snow has an insulating effect on the ground thermal regime, with a thinner snowpack favoring a cooler ground. A previous study by Hardy et al. (2001) [doi:10.1023/A:1013036803050] showed that low-snow winters lead to enhanced ground freezing in a hardwood forest. Other studies (Mellander et al., 2005 [doi:10.1016/j.agrformet.2005.08.008]; Stadler et al., 1996 [doi:10.1002/(SICI)1099-1085(199610)10:10%3C1293::AID-HYP461%3E3.0.CO;2-I]) have shown that the soil is cooler and frost is deeper under the canopy than in open stands or forest gaps. Thus, both low winter snowfall and canopy interception reduce snow accumulation on the ground, thereby reducing the insulating effect of the snowpack. However, both factors (low-snow conditions and canopy cover) have not been thoroughly investigated together in a single study. We address this in our observational study and we show that the difference in ground thermal regime is greater between gaps and subcanopy than between low-snow and normal winter conditions. We suggest a restructuring of the introductory paragraph dealing with these issues:

l. 42 to l. 55 (Introduction): "*It has been shown that the ground thermal regime is strongly influenced by the amount of snow accumulation (Zhang et al., 2005; Slater et al., 2017). In forests, the spatial pattern of soil temperatures is difficult to determine because snow depth is highly variable (Mellander*

et al., 2005). Observations from a subalpine forest plot in Switzerland show that frost penetrates the ground deeper under tree crowns due to less snow accumulation than in forest gaps which reduces the infiltration and increases surface runoff (Stadler et al., 1996). Infiltration is also limited during low-snow winters due to a thinner snowpack that favors soil freezing (Hardy and al., 2001; Shanley and Chalmers, 1999). It is clear that both canopy structure and snow conditions influence the ground thermal regime, soil freezing and infiltration. However, it is not well understood which of these two factors predominates over the other because they have not been investigated simultaneously in a single study."

We also propose the following addition to the Discussion:

l. 438 (Discussion): "***Our results are also consistent with Slater et al. (2017) as the effect of air temperature on ground temperature is more pronounced when the snowpack is shallow, which is specifically the case under canopy throughout W20-21.***"

b) The snow properties (effective conductivity) go a little way to mediating this influence, but are secondary in importance to the magnitude of the snow depth.

We disagree that the effective thermal conductivity of snow (k_s) is less important than snow depth for insulating the ground. In fact, snow height and k_s are rather of the same importance with regard to the thermal insulance of the snowpack (see Eq. 3 from Barrere et al. (2017)[doi: 10.5194/gmd-10-3461-2017]). The cooler ground under the canopy than in the gaps suggests that differences of snow height between the sites is greater than the difference of k_s. Unfortunately, we did not have simultaneous measurements of k_s at the same height in different the locations to quantify the contribution of k_s for insulating the ground.

c) In addition, earlier snowmelt meaning slower melt rates due to lower incoming shortwave just reinforces the point made by Musselman et al 2017 (as cited) and the lower SWE leading to lower stream discharge is intuitive.

Indeed, but our study allows us to quantify these processes with in-situ observations, in addition to shedding light on how these processes operate in two sub-environments of the humid boreal forest, i.e., gaps and subcanopy areas. This level of analysis at high temporal resolution, covering both snow and soil processes, has rarely been undertaken.

2. While comparisons between snow and soil properties in sub-canopy and forest gaps are consistently made, the explanation of these differences is often missing and makes the discussion highly speculative. This appears in the discussion section where the language used often relies on 'would imply', 'seemed to', 'may have', 'could be' or 'suggests that' to dilute the strength of conclusions that can be drawn.

   a) An atmosphere-forest-snow-soil model would allow the quantified explanation of processes that govern the observed snow/soil properties outcomes. While I respect the authors right to control the narrative, which is currently clearly expressed that this is an observational case study, the lack of a modelling approach hugely limits the capacity to quantifiably explain key processes and help to generalize beyond this catchment and beyond the two winters presented. In particular, the capacity to explore the forest canopy impact on interacting energy and mass balance processes (second objective on ln 71) would be unlocked. You have presented a fantastic snow and soil dataset, you have good forest canopy structure data using HPEval, so by including some process modelling (e.g. CRHM for hydrology or Crocus with a canopy model for snow properties) you would be able to more adeptly justify your explanations.

We agree that the addition of modeling would allow to generalize some of our results beyond what we found at the study site. We did indeed run simulations with a snow model (SNOWPACK version 3.6.0, see Bartelt and Lehning (2002) [doi:10.1016/S0165-232X(02)00074-5]) at this experimental site and at another site where we have a similar experimental setup. We decided not to include them for two main reasons:

- SNOWPACK (like many other snow models) uses a big-leaf approach to characterize the canopy, which means that the vegetation is represented as a homogeneous layer regardless of the structure of the canopy. This representation is not suitable for simulating snow in the gaps, which obeys different processes than under the canopy. This limitation would have prevented us from contrasting gap environments with areas under the canopy. Model improvements were found to be necessary for meeting the high level of details of our observations.
- Second, adding modeling development and model runs to our study would have greatly increased its already rich content, as we have 3 sites that are compared over two winters.

We have therefore decided to save our simulation results for a forthcoming manuscript that will focus exclusively on subcanopy environments.

It was also pointed out by the anonymous referee #1 that the second objective was not properly addressed in our study. Therefore, we have decided to drop this objective and address only the first one. We suggest the following modifications to the manuscript:

l. 69 to l. 76 (Introduction): "***The main research gap that motivates our work is that winter weather conditions and canopy structure have not been studied together to see how they influence snowmelt dynamics, the ground thermal regime, and the physical properties of the snowpack. Thus, the objective of this study*** *is to quantify the effect of a low-snow and warm winter* ***on the aforementioned processes*** *in a humid and discontinuous boreal forest. To assess this, we compared snow melt, snow physical properties, soil freezing, and spring runoff at a small catchment* ***in the south part of the*** *boreal forest of eastern Canada, for two consecutive winters. One winter was exceptionally warm and dry, while the other was colder, with precipitation amounts similar to the standard climatology of the study region. These contrasted conditions represent an ideal comparison to investigate some expected effects of climate change. Extensive snow monitoring and pit measurements were conducted to* ***achieve the research objective****.*"

l. 492 (Discussion): ***As the conclusions of this study are based solely on observations, it would be interesting to pursue analyses with models simulating water and energy exchanges at the atmosphere-forest-snow-soil interface. Multilayer snow models such as SNOWPACK (Bartelt and Lehning, 2002) or Crocus (Vionnet et al., 2012) would be good tools in that regard, as they are able to estimate water transport in a one-dimensional snow column and the infiltration into the soil.***"

We also suggest removing sentence from l.17 to l.19 in the abstract.

For example:

b) ln 421-422 states earlier melt onset suggests net radiation is lower, but this is not shown and the impact of sensible heat fluxes are not considered? Even in the sub-canopy where turbulence is lower, when the air temperatures go above zero then sensible heat fluxes can have a significant effect.

Thank you for this interesting remark. Indeed, turbulence is low under a forest canopy and turbulent fluxes are difficult to measure under these conditions (Reba et al., 2009 doi:10.1029/2008WR007045). Unfortunately, mainly for logistical reasons, we do not have such measurements. In the other hand, turbulent fluxes are also challenging to model under canopy and in forests gaps because the surface heterogeneity and discontinuity from forest edges make the Monin-Obukhov similarity theory invalid (Conway et al., 2018) [doi: 10.1175/JHM-D-18-0050.1]. However, we acknowledge that sensible heat flux can be significant under the canopy even without turbulence and therefore suggest the following changes to the manuscript:

l.421-422 (Discussion): "*An earlier melt onset implied that net radiation was lower in W20–21* ***(Fig. 5), which is consistent with a lower melt rate in that year (Fig. 6). Although it was not measured in this study, sensible heat flux may have contributed to snowmelt in gaps and under the canopy. This should be addressed in future modeling studies despite challenges in simulating turbulent fluxes in discontinuous forests (Conway et al., 2018).***"

c) On ln 428-429 you state that the structure of the canopy must be considered in models. I fully agree, and here but you have the capacity to show this in a model and address your own statement.

This is a good point. A model like FSM2 (see Mazzotti et al. (2020) [doi: 10.1029/2020WR027572]) has a detailed description of the canopy structure. This model can eventually be used with our measurements but the canopy structure at our study site should first be mapped to achieve accurate simulations with FSM2. We suggest the following change to the manuscript to make it less speculative:

l.428 to l. 430 (Discussion): *"Overall,* ***our results show that snowmelt dynamics are highly variable at the local scale in forests due to the discontinuous canopy structure. It underscores the importance of using high-resolution canopy structure mapping in snow models to accurately*** *predict* ***snowmelt in forests.****"*

d) A modelling approach would go some way to explain why heat loss was sufficient to favor soil freezing under a canopy but not in gaps (ln 434-435) – I would expect net LW to be important here, but comparison of modeled fluxes would allow a more robust analysis.

The ground freezes under the canopy because the heat lost to the snowpack is not compensated by the heat flux from the lower soil layers. Measurements of soil thermal conductivity (k_{soil}) made in the summer of 2021 at MF under the canopy with a Hukseflux TP02 heated needle probes give a k_{soil} of roughly 0.8 W m^{-1} K^{-1} (see comment 5). The temperature difference between depths of 5 and 20 cm is 1°C ± 0.2 °C from December to February both under canopy and inside forest gaps. We can therefore estimate an average heat flux entering the topmost 5 cm of soil from beneath between 4.3 and 6.4 W m^{-2}. This is larger than the ground heat flux at the soil-snow interface in the gaps, but lower than under canopy. Therefore, the topmost soil layers freeze in under the canopy but not in the gaps. We propose the following addition to the manuscript:

L. 434 (Discussion): "*Our observations show that the heat loss was sufficient to favor soil freezing under the canopy, but not in the forest gaps.* ***The topsoil thermal conductivity was measured at 0.8 W m^{-1} K^{-1} in the summer 2021 at the canopy station (Fig. S2). Given that the temperature difference between depths of 5 and 20 cm in the soil varies between 0.8 and 1.2 °C, we can readily estimate from Fourier's law applied to the top 5 cm of soil (Equation 5) that the average ground heat flux is 5.3 W m^{-2}. This is lower than the estimated snow heat flux under the canopy (Fig. 7e-f) which explains why the topmost subcanopy soil layers froze in both years.***"

e) If you couldn't manually assign an albedo class, which would be hard to do for purposes of spatial and temporal generalization, how would a modeled estimate of albedo affect the relative impact of energy and mass balance processes?

Indeed, such comparison would be interesting but unfortunately this goes beyond the scope of our study.

These are just a non-exhaustive number of examples where I feel inclusion of a simple modelling approach would allow the speculative areas of the discussion to be either removed or better justified.

In order to be coherent with our narrative, we would need a snow model that includes both a multi-layer description of the snowpack and a detailed representation of the canopy structure, which unfortunately, does not exist at the moment. Please see our response to comment 2a.

3. Much is made of winter 20-21 being analogous to a warmer climate, but while we should expect warmer winters in a warming climate, it is much less understood as to the impact on winter precipitation. This would have an impact on the mass of snow (see earlier comment) and the potential for rain on snow. Consequently, this could benefit from a much more robust underpinning using future model projections of climate (e.g. NA-CORDEX) to show not just where 20-21 fits within past measurements (nicely shown in Table 4), but where it lies in the future. Some big statements are currently being made (e.g. ln 464-465) about how snow thickness could override impacts of increased air temperatures. This could benefit from a more solid foundation in future climate projections.

Overall, the winter precipitation in eastern Canada is expected to increase in the future (Guay et al., 2015) [doi:10.1080/07011784.2015.1043583]. At the Montmorency Forest, we expect a slight increase of 4% in winter precipitation (ClimateData.ca, 2023) [https://climatedata.ca/, location Lac-Bureau). However, we also expect extreme winters, such as warm and low-snow winters, to be more frequent (Ouranos and MELCCFP, 2022) [https://cehq.gouv.qc.ca/atlas-hydroclimatique/]. This makes the warm and low-snow winter of 2020-21 at Montmorency Forest an interesting study case that illustrates a likely scenario. In order to address the two winters in this study relative to future climate, we suggest the following addition to the manuscript:

l. 238 (Results): "***In comparison, the projected DJF temperature and the total JFMA precipitation are expected to be –10.4 °C and 425 mm, respectively, by 2070 at the Montmorency Forest (ClimateData.ca, 2023).***"

Other changes were suggested related to the exceptionally warm and dry winter of 2020-21 in the context of the past and future climate. Please, see comment 1 of the document of responses to the anonymous referee #1 for the changes that we proposed.

4. The second objective features much less in the manuscript and is much more speculative (in its current form without hydrological modelling). It may be that this could be sacrificed in a revised manuscript in order to improve the focus on objective one?

We suggest dropping the second objective of the study (see comment 2a).

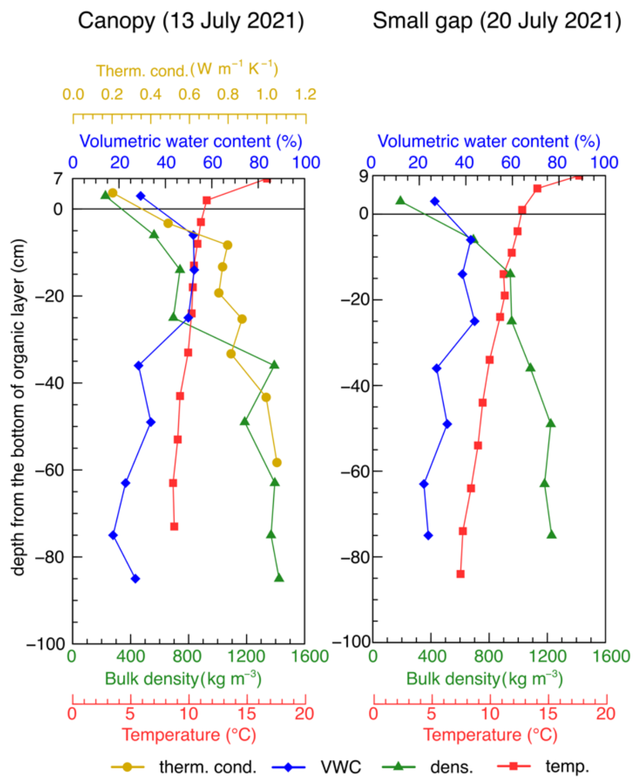
Minor comments

I appreciate the main thrust of my major comments (to include a modelling component) is non-trivial. Hence for now I will restrict the minor comments to a few obvious changes (also because the manuscript is well written and has very few obvious minor issues):

5. Ln 310-311: Are the soil profile characterizations (inc. porosity) shown anywhere? These may be important when considering soil hydraulics and thermal transfer.

Thank you for your comment. We do have soil profile characterization data. We suggest presenting them as supplementary material (Fig. S2) and introducing them as follow at the end of section 2.2.1.

l. 138 (Methods): "***We performed detailed soil profile measurements at the canopy and small gap sites on 13 and 20 July 2021, respectively. At the canopy site only, we measured soil thermal conductivity at different depths using a Hukseflux TP02 heating needle probe. Soil temperature was measured every 5 cm from the surface to 30 cm below and every 10 cm down to 80 cm below the surface with a Greinsinger Pt-1000 temperature probe (resolution: 0.1°C). Soil cores (≈165-cm^3) were taken from each layer, which were then weighted before and after oven drying for 48 hours at 65 °C and 100 °C for organic and mineral soils, respectively. This allowed to estimate the volumetric water content and the bulk density of the soil, assuming a density of water of 1000 kg m^3. Figure S2 presents the vertical profiles of soil characterization at both locations.***"



"***Figure S2: Soil profile characteristics measured at Montmorency Forest on 13 and 20 July 2021 at the canopy and the small gap stations, respectively. The plots include vertical profiles of thermal conductivity (at the canopy station only), volumetric water content, bulk soil density and temperature. The organic matter layer is 7-cm thick under the canopy and 9-cm thick in the small gap.***"

6. Ln 52; delete '17-19 May'

This reference was removed in the revised version of the manuscript that we suggest (see comment 1a).

7. Ln 168: ‘measurement’ rather than ‘measurements’.

Thank you, this typo will be corrected.

8. Ln 272: April rather than Avril.

This will also be corrected.

9. What evidence is there for the forest being humid? Particularly in the winter? No humidity measurements are presented or referred to.

This is a good remark. We described the boreal forest of eastern Canada as being humid based on the water availability index map (see Trabucco et al., (2019) [doi:10.6084/m9.figshare.7707605.v3], Figure 1a from D’Orangeville et al., (2015) [doi:10.1126/science.aaf4951]) and the work from Isabelle et al. (2020) [doi:10.1016/j.agrformet.2019.107813]. We suggest removing the sentence at lines 36 to 38 and changing to the manuscript as follow (see also comment 1a and 7 from the referee #1):

l. 38 to l. 41 (Introduction): “***Projections*** *for the boreal forest of eastern Canada*, ***characterized by humid and cold conditions in winter (D’orangeville et al., 2015; Isabelle et al., 2020),*** *point towards an increase in winter streamflow and an earlier spring freshet* ***with more snow accumulation in the north and less in the south (Guay et al., 2015). The interannual variability of precipitation and temperature is also projected to increase, making warm and dry winters more likely to happen in this region (MELCC, Ouranos 2022).***”