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 #1 (round 2)

We wish to thank anonymous reviewer #1 for commenting on the revised version of the manuscript and for providing additional insightful comments and suggestions. Based on these, we propose major changes to the Results and Discussion sections. We hope that these changes, if accepted, will place our results more clearly in context and better address the research objective. Our responses below are in blue, while excerpts from the manuscript are in blue *italics* with modifications in ***bold***.

Thank you for submitting the revised version of your manuscript. All my minor comments were well addressed in this revised version of the manuscript. Also, the major comments were mostly addressed but additional clarifications regarding my comments referring to the exceptionally dry year and the research gap are still needed.

Major comments

1. Discussion on how climate change impacts would deviate from your results and conclusions

The authors start the paper by highlighting that climate change will affect the boreal forest and that climate change impacts are difficult to assess in boreal forests because of its complexity (l.14-19). They use this as a motivation for the observational study, which will add knowledge about potential climate change impacts. At the end of the introduction you also mention the “contrasted conditions represent an ideal comparison to investigate some expected effects of climate change.”.

They come back to climate change in the conclusion “Although this work is limited to a two–year comparison within a small catchment, it highlights the many potential effects, all together, of a changing climate on snow hydrology in a discontinuous boreal forest through a unique set of highly detailed process–level observations.”.

You argue that due to higher variability such dry-warm years as winter 20-21 are becoming more likely. As you mentioned, however, winter precipitation is expected to increase in future. Thus, I would argue that dry-warm years will still be the exception in future. More likely are wetter-warmer years, with more rain and less snow. So, as you also acknowledged in your reply to the first revisions, winter 20-21 is not representative of the projected future. The climate change projections you added in lines 242-244 underline this. It shows that average winter precipitation is projected to be twice as high in future, compared to precipitation in winter 20-21, but the average temperature is projected to be similar to winter 20-21. Thus, such a low snow year will probably also be exceptional in future and more precipitation than in winter 20-21 will be normal.

Therefore, I think you need to mention better in your discussion that the conditions during your study resemble a condition that is more likely in future but that will not be the norm. Therefore, I think you need to add to the discussion some sentences about how your results differ compared to projected average future conditions, especially since you use climate change as a predominant motivation for your study. What would be different if winter precipitation would be higher (wet-warm year)? Would there be probably more snow than in your results? More ROFs? How would this affect the processes you discuss?

As mentioned by the reviewer, since the projected increase in precipitation will be combined with an increase in temperature, it is expected that liquid precipitation will increase in winter at the expense of solid precipitation. Therefore, the number of days with snow and the maximum snow accumulation in winter will likely decrease (see Fig.8 from Guay et al. (2015) [doi:10.1080/07011784.2015.1043583]). Although the low precipitation that we observed in W20-21 is not consistent with the climate change projections, the observed low snowfall and low snow accumulation on the ground in W20-21 is. This should be the main justification for considering W20-21 as representative of future winters, complemented by the interannual meteorological variability.

With respect to wet and warm winters, we expect an increase in the likelihood of ROS events and a decrease in solid precipitation. Therefore, the snowpack thickness would be less than in a normal winter. Since the snowpack thickness exerts a control on the ground thermal regime and on snow metamorphism, it is reasonable to expect that the processes described in this manuscript would not differ much in a warm and wet winter. However, this remains speculative and a third winter of observations (warm and wet) would be needed to confirm this hypothesis.

Overall, we agree that W20-21 should be placed more clearly in the context of climate projections for eastern Canada, based on temperature and snow cover duration and thickness. Therefore, we propose the following changes to the manuscript:

l. 14 to 15 (Abstract): "*In the boreal forest of eastern Canada, winter temperatures are projected to increase substantially by 2100.* ***This*** *region is also* ***expected to receive less solid*** *precipitation, resulting in a reduction in snow cover thickness and duration.*"

l. 439 to 446 (Discussion): "*In eastern Canada, as in other high-latitude and high-elevation regions, the snow cover extent is expected to decrease due to warmer winter temperatures (Guay et al., 2015; Pepin et al., 2015; Kunkel et al., 2016).* ***This region is also expected to receive more winter precipitation in the future (Guay et al., 2015; Ouranos and MELCCFP, 2022). Therefore, the exceptionally warm and dry conditions observed at MF in W2020-21 are not entirely consistent with the median climate projections for eastern Canada. However, these conditions did result in a snowpack that melted out 23 days earlier and in a maximum snow height that was 36% lower than the 1982-2022 reference period (Table 4). Based on these low snow accumulation conditions, the winter of 2020-21 is representative of what can be expected in eastern Canada with climate change even though the expected more abundant liquid precipitation may lead to more significant snowpack modifications than observed in W20-21.***"

2. Research Objective

The revised introduction is well written. As main research gap that motivates your study, you mention that weather conditions and canopy structure have not been studied together to see their influence (l. 62-64). Before in the introduction you mention that it is not well understood "which of the two factors predominates because they have not been investigated simultaneously in a single study" (l.57-58).

Although the objective of the study is much clearer in this version of the manuscript, I do not have the feeling you addressed clearly which factor (canopy structure or weather) predominates in the investigated processes. To fully address the research gap a paragraph could be added to the discussion which discusses the two factors (weather and canopy structure) and the relationship between them that you can draw/hypothesize based on your results, e.g. what affects the snow dynamics, the ground thermal regime, and the physical properties of the snowpack more, the complex structure of the canopy or the climate conditions?

Thank you for this very good suggestion. Based on this, we decided to compare canopy and gap locations using several parameters: maximum snow height, snow surface temperature, melt-out date, ground heat flux, ground temperature, vertical temperature gradient and density, SSA and snow permeability profiles. This comparison shows that the meteorological forcing exerts a stronger control on the snow accumulation and melt dynamics, that forest structure controls the freezing of the top-most soil layers and that both meteorological forcing and forest structure produce significant differences in the snowpack physical properties. We propose the following additions to the manuscript in the Abstract and in the Results and Discussion sections:

l. 26 to 28 (Abstract): “***Our results highlight that snow accumulation and melt dynamics are controlled by meteorological conditions, soil freezing by forest structure, and snow properties by both weather forcing and canopy discontinuity.***”

l. 287 to 294 (Results): “*Due to a lower snowfall, the* ***maximum snow height ($H_{s,max}$)*** *in W20–21 was on average 44%* ***lower*** *than in the reference winter (Fig. 3).* ***As*** *the air was warmer in W20–21,* ***the snow surface temperature (SST) was on average 1.35 °C warmer than in the reference winter (Fig. 4).*** *In contrast, because there was less snow on the ground in W20–21, heat transfer through the snow was facilitated, resulting in the lowermost snow layers being colder than in W21–22. Due to canopy interception, less snow accumulated under the trees than in the gaps in both years and* ***the $H_{s,max}$ was on average 35% lower under the canopy than inside both gaps.*** *Interestingly, topmost snow layers appear to be colder under the canopy than inside gaps. This is in contradiction with Fig. 4,* ***which shows that the SST was*** *higher under the canopy than inside gaps* ***in both years (+1.53 °C)****, despite similar air temperature at all three stations. This discrepancy is further discussed in Sect. 4.2.*

l. 318 to 322 (Results): “*From W20–21 to W21–22, the duration of the melt period slightly decreased from 31 to 26 days and from 37 to 29 days in the medium and small gaps, respectively, whereas it did not change under the canopy* ***(24 days)****.* ***The melt-out date was on average 19 days earlier in the warm year for all sites. In comparison, the difference in melt-out date between the canopy and gap stations was much smaller, with snow melting on average 5 days earlier under the canopy in both years.***”

l. 328 to 329 (Results): “*The* ***ground heat flux*** *(GHF) in DJF was on average 50% higher in W20–21 than in the reference winter (Fig. 7). The largest difference was observed under the canopy, where the GHF was* ***significantly*** *larger than in gaps in W20–21 and in W21–22.*”

l. 355 to 360 (Results): “*From November to January, the average $|\partial T/\partial z|$ was similar at each site and year,* ***except under the canopy where the gradient was much larger during the warm year*** *(Fig. 9). In February and March of the low–snow and warm winter, $|\partial T/\partial z|$ remained within or above the transition zone from equilibrium to kinetic crystal growth (Colbeck, 1983). In contrast, in February of the reference winter, the decrease of $|\partial T/\partial z|$ was more intense and we observed a drop of $|\partial T/\partial z|$ below 10°C m^{-1} in gaps. $|\partial T/\partial z|$ was also higher under the canopy than in gaps****, in particular before February where the canopy-gaps difference is much stronger****.*”

l. 380 to 382 (Results): “*Kruskal-Wallis tests performed on density measurements showed that the density difference between both winters* ***at all sites*** *was significant,* ***as well as the canopy-gaps density difference in both winters*** *(p-value < 0.05).*”

l. 391 to 393 (Results): “*Note that in both years, the SSA and the snow permeability was lower and higher, respectively, under the canopy than in gaps* ***for the middle half of the snowpack. This difference was also significant based on a Kruskal-Wallis test (p-value < 0.05).***”

l. 531 to 550 (Discussion): “***4.5 Meteorological conditions versus forest structure***

A larger difference in $H_{s,max}$ between the two years than between the sites suggests that weather conditions had a greater effect on the snow accumulation than forest structure. Lower snow accumulation at the onset of snowmelt in the warm year compensated for the much slower melt than in the reference year, so the difference in snowmelt duration between both years was less pronounced than the difference between the sites. Since weather conditions also controlled the onset of the melt period, as indicated by snowmelt starting on the same day at all sites in each year, we observed a melt-out date difference that was much greater between years than between sites. Overall, this suggests that the meteorological forcing was more important in influencing snow accumulation and melt than the canopy structure.

One might also expect that the difference in soil temperature between years would be more pronounced than between sites, as a consequence of a greater difference in snow height. However, our results show the opposite. In fact, the evolution of the soil temperature followed a similar pattern in both years, with a slightly lower temperature in the warm year for a given depth. In contrast, the differences in soil temperature between gap and canopy sites were much more pronounced, in particular near the ground surface, with freezing observed only under the trees. This suggests that the forest structure had a stronger influence on the soil thermal regime than the weather conditions at this study site during these two years.

A larger difference in $|\partial T/\partial z|$ between gaps and canopy sites than between W20-21 and W21-22 from November to January indicates that the canopy structure had a strong influence on the $|\partial T/\partial z|$. However, the difference in $|\partial T/\partial z|$ between both years became more pronounced in February and March, which also suggests that the relative influence of weather conditions on the temperature gradient increases during winter. Since the differences in snow density, SSA and K_s between gaps and canopy and between seasons were all significant, we cannot distinguish which factor (meteorological conditions and forest structure) dominates regarding the evolution of snow properties."

Minor Comments

3. l. 242-244: It's good that you mention what temperatures and precipitation are expected. However, it is also important to mention which emission scenario is used for generating these projections and whether these are ensemble projections of multiple GCMs.

Thank you for that observation. We used the SSP5-8.5 emission scenario based on the CMIP6 climate simulations to obtain the temperature and climate projections to 2070 at our study site. We suggest the following change to the manuscript:

l. 263 to 266 (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****, based on the SSP5-8.5 emission scenario from CMIP6 climate simulations*** *(ClimateData.ca, 2023).*"

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 (round 2)

We would like to thank the anonymous reviewer #2 for complementing on his/her previous comments. Based on these new comments, we plan to make significant changes to the manuscript. First, we propose to deepen the comparison with the study by Slater et al. (2017) in the Discussion. Second, we also propose to include SNOWPACK modeling results in the manuscript, which we hope will provide a clearer explanation of the observed processes. Our responses below are in blue, while excerpts from the manuscript are in *italic* with changes in ***bold.***

I would like to thank the author for making changes to their manuscript in light of the two reviews. In particular, removing the second objective from the original manuscript has helped improve the focus of the study. There are two outstanding comments that I feel would improve the paper.

Major comments

1. The addition of text using Slater et al. (2017) is welcomed. However, your response that effective conductivity is not less important than snow depth, is not shown by Figure 3 in Slater et. al. (2017). The relationship is dominated by snow depth, while the noise around it is likely due to snowpack properties. If snow properties were more important than snow depth, then there would be no relationship of this sort. Arctic tundra snowpacks, like Bylot Island (Barrere et al. 2017, 10.5194/gmd-10-3461-2017) where proportions of wind slab and depth hoar play a very important role in bulk thermal conductivity, will contribute to the variability around the relationship in Slater et al. (2017). However, the range of latitudes used by Slater et al. (2017), see Fig 2, aggregates lots of lower latitude snowpacks of the type expected in Montmorency Forest. I would expect snowpacks of the type measured in Montmorency Forest to be more closely related to snow depth. It would be nice if the authors could consider adding the gist of this to their discussion so that the implications of their work in Montmorency can be put in context of forest snowpacks in general.

As noted by Slater et al. (2017), the significant scatter in the data points in Fig. 3 could be due to climate variability, snow metamorphism patterns, soil moisture properties and measurement uncertainties. We agree with the reviewer that the effective thermal conductivity of snow (k_s) could contribute to the scatter, while maintaining an exponential increase in the normalized air-soil temperature difference. However, Slater et al. (2017) do not quantify the role of k_s in their model of snow thermal insulation. Also, the study does not integrate data points from the boreal region of eastern Canada, which is characterized by cold and humid conditions. However, we believe it is insightful to apply the methodology of Slater et al. (2017) to our winter site and compare our observations to their dataset:

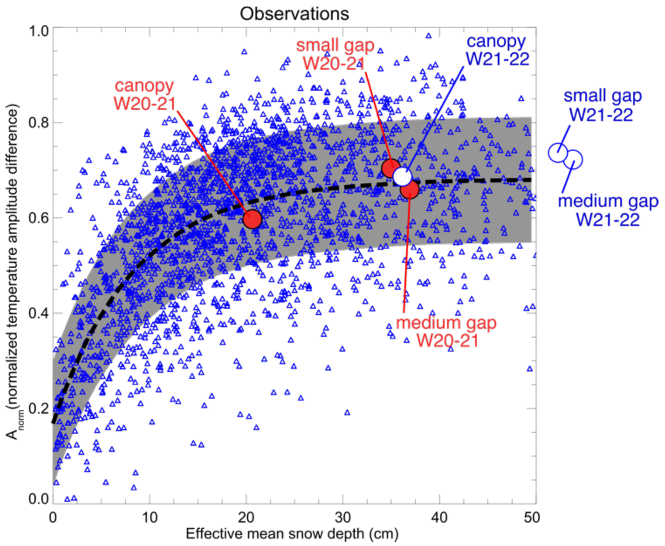


Fig. R1: Figure 3 from Slater et al. (2017) showing the observed relation between normalized temperature amplitude difference (A_{norm}) and the effective mean snow depth along with the resulting exponential fit (dashed line) and our data points. The grey shading shows the median fit plus/minus the mean scatter of all fits. Red dots show the warm and low-snow winter while white dots show the reference year.

Our data points fall within the scatter of Fig. 3 from Slater et al. (2017) and follow the observational fit shown in the figure. Our data points cover a large range of effective mean snow depth, but a much smaller range of normalized temperature amplitude difference (A_{norm}). This suggests that even in an exceptionally low-snow and warm year, the air and soil temperatures in a site like the Montmorency Forest (MF) are decoupled under the canopy and within forest gaps. This further supports our observations that weather conditions have only little effect on the soil thermal regime. Overall, we suggest the following changes to the manuscript:

l. 494 to 502 (Discussion): "*Slater et al. (2017)* ***assessed the influence of snow depth on the decoupling of seasonal air and soil temperature amplitudes from multiple locations in the Northern Hemisphere. Although this study does not include sites from eastern Canada, we chose to compare our results with the observations presented in Fig. 3 from their paper. We observed that air and soil seasonal temperature signal decouples in both years at all three locations. This supports our previous findings that the exceptional low-snow and warm conditions met in winter 20-21 had almost no effect on the thermal insulation between the soil and the air due to thickness and properties of the snow (Fig. 7; Table 5). The increased snow faceting in W20-21 may also have contributed to a more efficient insulation of the ground despite a thinner snow cover.***"

2. The original comment that "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", still remains. Consequently, the suggestion to use an atmosphere-forest-snow-soil model would allow the quantified explanation of processes that govern the observed snow/soil properties, is still valid.

While big-leaf approaches are not an ideal way to represent the forest canopy, many modeling approaches still use these successfully with two or more simple parameters to represent shortwave extinction and longwave emittance. This would still be of use. However, what would be better, would be to use the more sophisticated two-layer canopy approach of Gouttevin et al. (2015) 10.5194/gmd-8-2379-2015, which the authors have used in their paper currently under discussion in The Cryosphere (10.5194/egusphere-2023-3012) and which they allude to in their response. A two-

> layer forest canopy model coupled to SNOWPACK (as per Gouttevin et al. 2015) would very adequately allow the impacts on snowpack structure to be investigated in the manner suggested in the first review. The readers of this manuscript in HESS would benefit enormously from including model results which would allow greater explanation of differences between sub-canopy and forest gaps and provide stronger conclusions that could more easily be generalized

We acknowledge that the use of SNOWPACK with the two-layer canopy would provide complementary explanations for the hydrological processes studied. Although this model resolves the subcanopy longwave radiation well (Gouttevin et al., 2015, doi: 10.5194/gmd-8-2379-2015; Todt et al., 2018, doi:10.1029/2018JD028719), SNOWPACK is not parameterized to simulate snow-forest processes in forest gaps (i.e., direct throughfall, shortwave extinction, longwave emissions from the gap edges and wind speed attenuation). One could simulate snow in an open site, but this would not be representative of the gap snowpack. Implementation of HPEval (Jonas et al., 2020, doi:10.1016/j.agrformet.2020.107903) into the two-layer canopy scheme of SNOWPACK may help to improve the representation of shortwave transmission in gaps. However, this would rather require significant changes to the model. Such developments are beyond the scope of this short addition to the paper here and should be the subject of a separate study.

Given the limitations described above, we propose to use SNOWPACK with the two-layer canopy to compare the melt period of the warm/low-snow year with the reference year for the snowpack under the canopy. This allows the study of some processes and variables that are difficult to analyze with observations alone. A such, we propose to include simulations of snowpack runoff, liquid water content and basal ice layer formation to the observations presented in Figure 11. We would use the same initial canopy parameterization as presented in our paper discussed in The Cryosphere (10.5194/egusphere-2023-3012). We propose the following changes to the manuscript:

l. 1 to 3 (Title): "*How does a warm and low–snow winter impact the snow cover dynamics in a humid and discontinuous boreal forest?* ***Insights from observations and modeling in eastern Canada*****"**

l. 18 to 21 (Abstract): "*In this study, we assess the influence of a low–snow and warm winter on snowmelt dynamics, soil freezing, snowpack properties, and spring streamflow in a humid and discontinuous boreal catchment of eastern Canada (47.29° N, 71.17° W, ≈ 850 m ASL)* ***based on observations and SNOWPACK simulations****.***"**

l. 28 to 30 (Abstract): "*Overall, observations and simulations suggest that the exceptionally low spring streamflow in W20-21 was mainly driven by low snow accumulation, slow snowmelt and low precipitation in April and May rather than enhanced percolation through the snowpack and soil freezing.*"

l. 70 to 72 (Introduction): "*Extensive snow monitoring and pit measurements****, supported by multi-layer snowpack simulations under the canopy,*** *were conducted to achieve the research objective.*

Section 2 presents the study site, the instrumentation, the observed and estimated physical variables ***and the modeling setup****.***"**

l. 74 to 76 (Introduction): "*The simulated water content profile and runoff from the snowpack and the measured* *spring streamflow of the catchment* ***are*** *also presented for both winters in Sect. 3***"**

l. 235 to 254 (Methods): “*2.4 Modeling setup*

We simulate the snowpack using the SNOWPACK model, version 3.6.0 (Lehning et al., 2002), coupled with the two-layer canopy module implemented by Gouttevin et al. (2015) for winter 20-21 and winter 21-22. SNOWPACK is a multilayer snow model that solves Richards equations for liquid water transport in the snowpack (Wever et al., 2014). The two-layer canopy scheme has shown a reasonably good performance in simulating the thermal inertia of the canopy and the underlying snowpack (Gouttevin et al., 2015; Todt et al., 2018; Bouchard et al., 2024). The SNOWPACK canopy module does not simulate the heterogeneous structure of the canopy, so snow-forest processes within forest gaps are not parameterized in the model. Therefore, we used the simulations described in Bouchard et al. (2024), referred to by the authors as the "Initial Module", for winters 20-21 and 21-22 at the MF site.

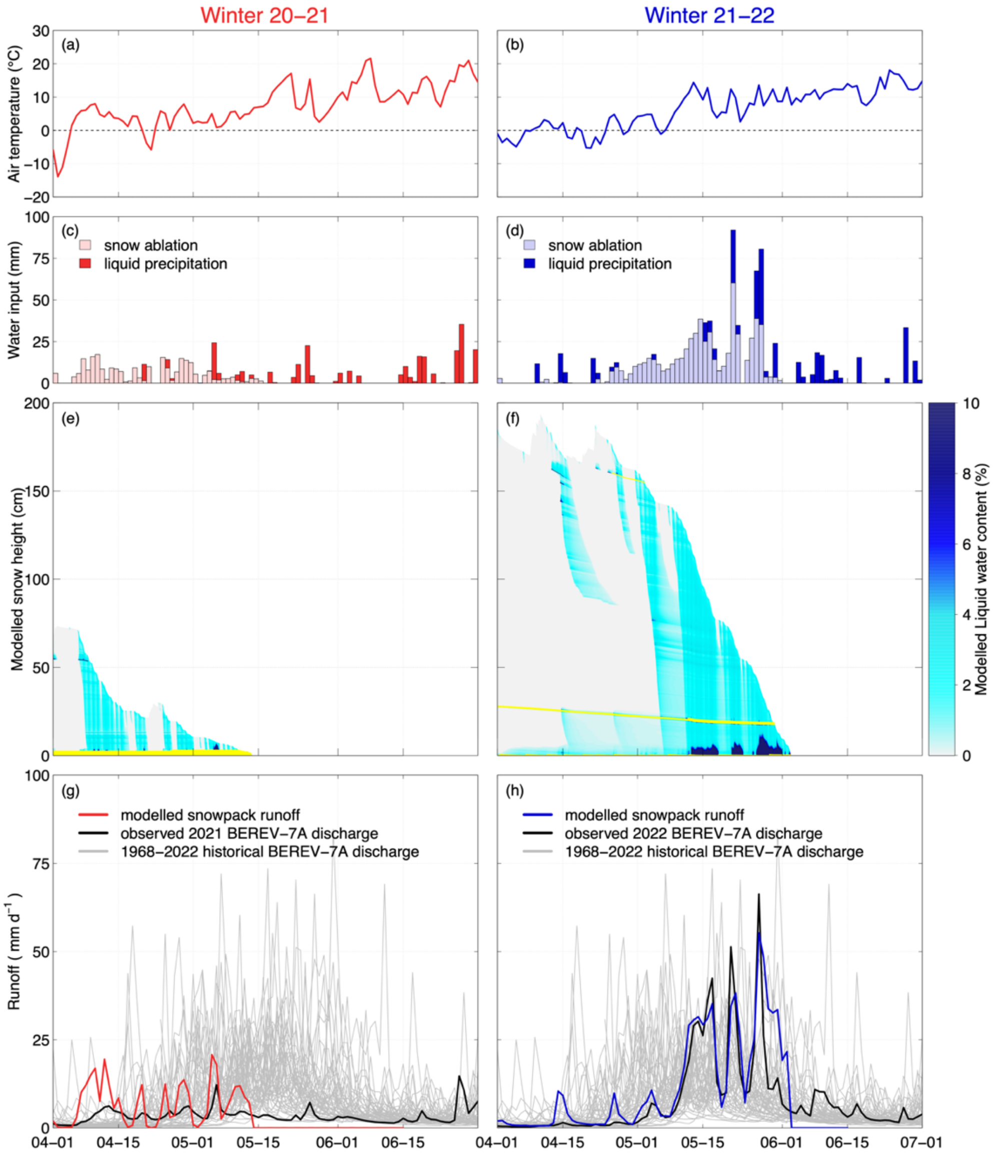
Briefly, simulations were performed at a 15 min time step using local meteorological forcing data measured above the canopy thanks to a 20 m flux tower and recorded at a 30 min time step (Isabelle et al., 2018). We also used measurements from a double fence automatic reference for precipitation inputs (Pierre et al., 2019). Based on field measurements, the tree height and the leaf area index (LAI) were set to 9.2 m and 4.8 m^2 m^{-2}, respectively. The stand basal area was set to 0.005 m^2 m^{-2} based on Hadiwijaya et al. (2020). The direct throughfall fraction was set to 0 to better represent the subcanopy snowpack. We used values from Gouttevin et al. (2015) for the canopy albedo and the two-layer LAI fraction. Finally, the initial soil parameterization was based on field measurements taken in the summer of 2021. Additional details on the forcing data, the initial canopy and soil parameterization, and the SNOWPACK initialization file are provided in the Methods section of Bouchard et al. (2024). Note that the authors found a good agreement between the simulations and observations for snow cover height and duration, snow surface temperature and snow density profiles using this modeling setup. This demonstrates that the model is suitable for simulating the canopy snowpack at the MF site.”

l. 395 to 414 (Results): “*In 2021, air temperatures became positive in early April, allowing a decline in SWE. In 2022, this occurred 20 days later (Fig. 11**a-b**). The daily melt rate was much smaller in the first winter than in the second, as already shown in Fig. 6. In April and May, rain-on-snow accounted for 54 mm in 2021 compared to 202 mm the following year* ***(Fig. 11c-d).***

Consistent with our observations, the simulated subcanopy snowpack was much thinner at the onset of snowmelt in 2021 than in 2022 (Fig. 11e-f). The wetting front simulated by SNOWPACK in winter 20-21 took 57 h at an average rate of 30 cm d^{-1} to reach the ground in early April, while it took 149 h at 26 cm d^{-1} in early May the following year. The model also simulated a thick basal ice layer in W20-21 and a thin ice layer deep in the snowpack in W21-22, which is also in line with snow pit observations (Fig. 10i).

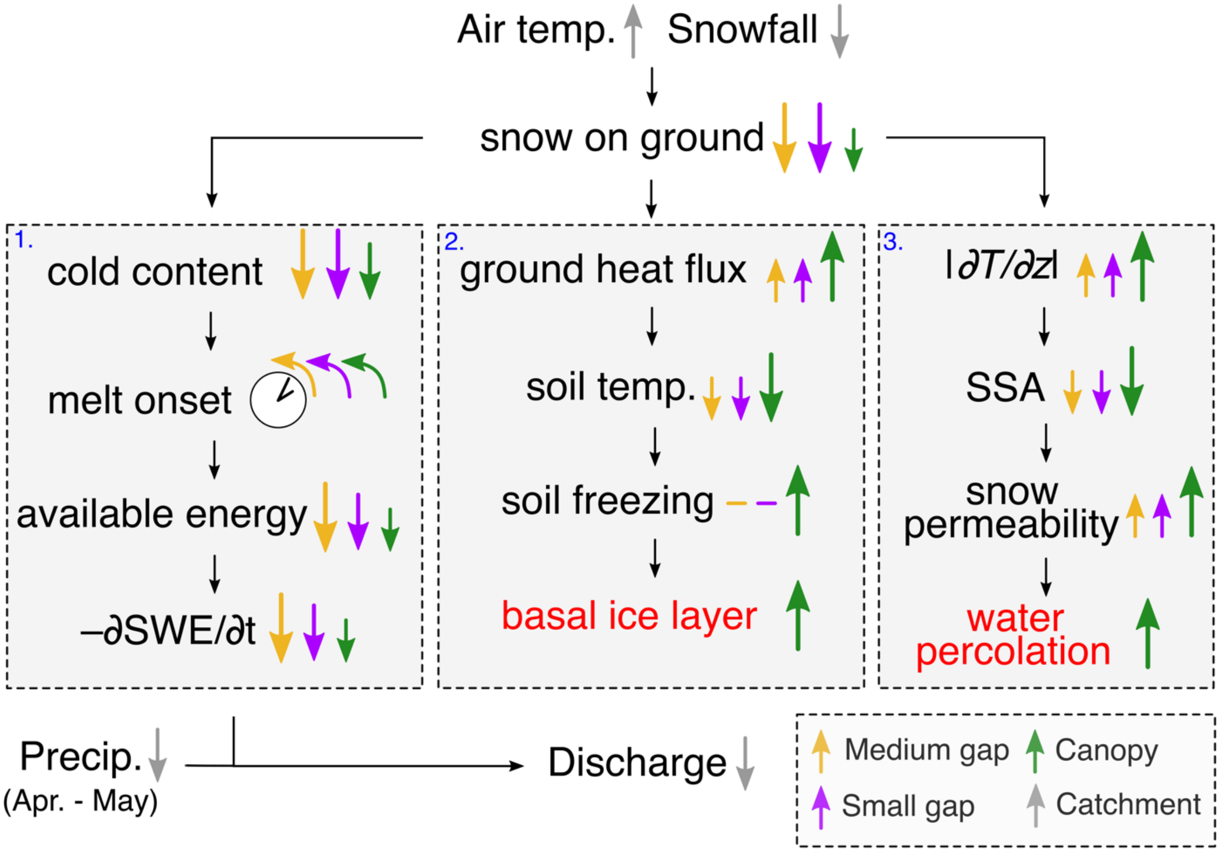
Besides modeling a much earlier snowpack runoff, the model simulated spring runoff with quite different patterns in both years (Fig. 11g-h). In 2021, SNOWPACK generated intermittent runoff driven by several episodes of refreezing of the entire snow column, while in 2022 the simulations resulted in a continuous runoff throughout the snowmelt period, with peaks driven by liquid precipitation. The runoff simulations in both years are generally consistent with the observations of discharge at the outlet of BEREV-7A catchment. In 2021, the measured discharge was generally lower than the simulated runoff and slightly delayed. This was also the case in April 2022. However, during the snowmelt of 2022, the discharge measurements were similar to or greater than the simulated snowpack runoff in 2022, and the observed and simulated runoff peaks were synchronized.

Overall, low *snowmelt and* ***low*** *liquid precipitation* ***in the spring of the first year*** *resulted in significantly lower* ***spring streamflow runoff*** *than in the second* ***year****. In April and May 2021, the average runoff was 3.1 mm* d^{-1} *compared to 8.5 mm* d^{-1} *in the following year. The spring runoff from the low–snow and warm winter was the lowest observed at the outlet of BEREV-7A for April and May since discharge monitoring began in 1968. In 2022, it was the sixth highest.****”***



l. 415 to 422 (Results): *Figure 11: Air temperature (a–b), daily difference* ***in*** *SWE, liquid precipitation (c–d),* ***modeled snowpack liquid water content (e-f), simulated snowpack runoff and observed*** *streamflow discharge* ***(g-h)*** *for winter 20–21 (left) and 21–22 (right). Air temperature and liquid precipitation are measured at the NEIGE site,* ***located*** *some 4 km north of the main study site* ***and about 200 m lower in elevation.*** *SWE is averaged for the canopy (75%), small gap (12.5%)****,*** *and medium gap (12.5%) stations for representativeness of the study catchment.* ***SNOWPACK simulations are representative of the subcanopy snowpack only.*** *The streamflow discharge is monitored at the outlet of the BEREV-7A catchment.* ***Ice layers are shown in yellow in (e) and (f), while the gray lines*** *in* ***(g)*** *and* ***(h)*** *show historical measurements over the 1968–2022 period.”*

l. 424 to 429 (Discussion): *"So far, our observations show that the low–snow and warm winter of 2020–2021 led to a slower melt, colder ground, enhanced gradient metamorphism and ultimately to a reduced and less intense spring freshet than the reference winter of 2021–2022.* ***We used the SNOWPACK model to support our observational results under the canopy regarding the formation of a basal ice layer, downward liquid water transport in the snowpack and the resulting runoff in spring. Note that*** *there are important nuances to consider with respect to forest gaps and subcanopy snowpacks. Figure 12 provides a conceptual summary of our* ***results****."*



l. 430 to 437 (Discussion): "*Figure 12: Summary of the results. Upward arrows correspond to an increase and downward arrows to a decrease in the low–snow and warm winter with respect to the reference winter. The clock with counterclockwise arrows means that the process happens earlier.* ***Results obtained from SNOWPACK simulations are in red.*** *The yellow, purple, and green arrows indicate the effects in the medium gap, the small gap and under the canopy, respectively. The size of the arrows indicates the magnitude of the process at one location relative to the others. Large gray arrows indicate an analysis made for the entire catchment. Small black arrows show the causal link between the observations processes. Gray boxes refer to processes treated in this study (1. snowmelt dynamics; 2. soil thermal regime; 3. snow metamorphism).*"

l. 482 to 487 (Discussion): "*A thinner snowpack* ***in the low–snow winter*** *allows more heat loss from the ground to the atmosphere, and as such, a larger ground heat flux,* ***which*** *led to a cooler soil than for the reference winter (Fig. 7; Table 5).* ***Under the canopy, this*** *phenomenon was intensified* ***as indicated by subzero temperatures in the top 5 cm of soil in both years. These observations are supported by a modeled basal ice layer in both years, the formation of which is favored by a frozen soil (Albert and Hardy 1993; Westermann 2011). The thicker simulated ice layer in W20-21 is consistent with the***

enhanced soil freezing observed in that year. Overall, our results suggest *that the heat loss was sufficient to favor soil freezing under the canopy, but not in the forest gaps.*"

l. 516 to 519 (Discussion): "*A thinner snowpack also led to higher vertical temperature gradients (|∂T/∂z|) in the low–snow and warm winter (Fig. 9), resulting in more pronounced faceting, lower SSA, and a higher permeability (K_s) than in W21–22 (Fig. 10).* ***SNOWPACK simulations suggest that the enhanced gradient metamorphism in W20-21 resulted in a slightly faster water percolation in the snow cover.***"

l. 551 to 570 (Discussion): "***4.6*** *Reduced spring streamflow*

Figure 11 clearly show that the spring freshet was earlier and reduced in the low–snow and warm winter compared to the reference winter. ***Both modeling and observational results*** *support that an earlier and slower melt exerted a major influence on streamflow regime,* ***which is*** *consistent with the work of Musselman et al. (2017)* ***in the western United States****.* ***A thinner snowpack in the warm year mainly explains why the wetting front in the SNOWPACK simulations reached the ground much faster than in the reference year. The modeled percolation rate was slightly higher in W20-21 than in W21-22, but this difference remains small compared to the difference in snowmelt timing between the two years. Also, the observed and simulated thicker basal ice formation in W20-21 did not result in a faster hydrological response at the outlet of the catchment, as might be expected.***

The large difference in spring runoff between the two years ***can further be attributed to lower precipitation as ROS in the spring of the warm year****. Indeed, ROS accumulation was nearly four times lower* ***in W20-21*** *than* ***in W21-22****. This can be attributed to dryer conditions in spring (Fig. 2a) and also to a short–lived snowpack, limiting the exposure of the snowpack to rainfall in spring (Cohen et al., 2015).* ***The delayed and lower discharge response to modeled snowpack runoff in W20-21 suggests that some of the meltwater and liquid precipitation infiltrated into an unsaturated soil and recharged the aquifer (Schilling et al., 2021). It is likely that this also happened in April of 2022, before snowmelt (Fig. 11h). In contrast, the higher discharge, which was also synchronized with snowpack runoff simulations, suggest that the soil was saturated and subsurface flow contributed to a greater streamflow discharge during the 2022 snowmelt. These contrasting results are not surprising given that the spring daily water input was often much higher in 2022 than in 2021. Overall, i****n light of our* ***observations and SNOWPACK simulations****, it appears that* ***the effects of*** *both soil freezing and snow structure* ***on the timing and amplitude of runoff are of secondary importance compared to the influence of an earlier and slower snowmelt and spring liquid precipitation.***"

l. 586 to 590 (Discussion): *"****Although the SNOWPACK model allowed for a more thorough interpretation of the hydrological influence of snow properties, the simulations were limited to subcanopy locations. Coupling a multilayer snow model, such as SNOWPACK or Crocus (Vionnet et al., 2012), with a detailed representation of canopy structure, such as that found in FSM2 (Mazzotti et al., 2020), would be required to properly simulate snowpack evolution in forest gaps. Recent work by Mazzotti et al. (2023) is promising in this regard.****"*

l. 612 (Conclusion): *"Using dedicated field observations,* ***along with SNOWPACK simulations,*** *we investigated…"*

l. 621 to 622 (Conclusion): *"Although enhanced soil freezing and larger snow permeability,* ***supported by simulations of a thicker basal ice layer and faster percolation,*** *point toward…"*

l. 631 to 633 (Code and data availability.): "*Documented code of SNOWPACK version 3.6.0 is available on GitLab (https://gitlabext.wsl.ch/snow-models/snowpack).* *Data from snow pit measurements and from the monitoring stations in the medium and small gaps, and under the canopy are freely available at https://doi.org/10.5281/zenodo.8213204.***"**

l. 634 to 635 (Authors contribution): *"BB* ***ran the simulations and*** *conducted the analysis of the results with inputs from DFN, FD, FA, and TJ."*

DOI of the new references cited:

- Bouchard et al., 2024 (doi:10.5194/egusphere-2023-3012)
- Gouttevin et al., 2015 (doi:10.5194/gmd-8-2379-2015)
- Hadiwijaya et al., 2020 (doi:10.3390/f11020237)
- Isabelle et al., 2018 (doi:10.1016/j.agrformet.2018.07.022)
- Lehning et al., 2002 (doi:10.1016/S0165-232X(02)00073-3)
- Mazzotti et al., 2020 (doi:10.1029/2019WR026129)
- Mazzotti et al., 2023 (doi:10.5194/egusphere-2023-2781)
- Todt et al., 2018 (doi:10.1029/2018JD028719)
- Westermann et al., 2011 (doi:10.5194/tc-5-945-2011
- Wever et al., 2014 (doi:10.5194/tc-8-257-2014)